

INTEGRATED OPTIMIZATION OF OPERATIONAL AND TACTICAL PLANNING FOR LOG PRODUCTION

By

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Abstract

Log merchandising, which involves scheduling of stand harvests, planning stem conversion strategies, and market planning for logs, are some of most important decisions made in the management of a resource. Much research attention has focused on developing modelling methodologies for components of log merchandising decision making. However, many planning approaches either do not have the capability to solve these decisions in an integrated manner, or are suitable for making integrated decisions, but only for single time period. Non integrated and single period models cannot be used for evaluating trade-offs between timing of stand harvest and stem conversion strategies in a flexible manner. As a Consequence, such systems can fail to identify merchandising strategies which offer the greatest opportunity benefits.

There are two separate considerations in the integration of such plans. The first is the integration of planning across all temporal levels of decision making, while the other is integration of log production planning for all the stands in a forest estate. In this study, a planning framework was adopted which enables the log merchandising decisions to be solved in an integrated manner. The adopted modelling framework comprises three hierarchical levels: a medium term tactical model, a short term tactical model, and an operational scheduling model.

The medium term tactical model is similar to the many harvest scheduling models in forestry literature, and addresses issues of sustainability of production, regulatory requirements, and preliminary scheduling of log production over a medium term horizon. The short term tactical model disaggregates the medium term plan into detailed production plans, with stands, group of logging settings, or logging settings as the production units. The model also addresses issues of harvesting system availability, and the optimal location of landings. This model was not developed in the study, but a modelling approach recommended for solving this level is a mixed integer model based on facility location theory, interfaced to a Geographical Information System (GIS) for generating feasible logging layouts and for presentation of reports.

The operational allocation model solves for optimal scheduling of harvesting systems to production units (settings), and also develops detailed log mix production and allocation plans. The problem is formulated as a mixed integer model, with the integer variables representing possible crew allocations, and is solved with commercial mathematical programming packages. The models are integrated with the hierarchical planning paradigm, in which separate models are developed for each decision level, with higher level plans forming part of constraints to plans at the lower levels.

A yield description system was developed, which enables the evaluation of log production plans to be conducted in an integrated fashion. The method involves estimating the yield potential of a stand by a few aggregated stem quality classes with a bucking model. The values of the log classes used to specify product preferences in the evaluation, are defined as those which yield maximum volume of a class, without leading to a reduction in the yield of higher quality classes. Planning of outturn from each stand is then determined by disaggregating the log quality class into market log types with similar quality requirements, the formulation for which is built into optimization models for the various decision levels. In the determination of log mix to be produced, downgrading is employed as a marketing strategy and for balancing demand and supply by log assortments, a capability that is built into the models.

A method was developed for controlling outturn during field implementation. The method involves the iterative revision of log specification variables for each stand, to determine new ones that lead to a satisfactory realization of log production targets. When used in field implementation, the new specifications should result in improved achievement of log production targets, and in reduced variability in the quality of material of each log assortment in a shipment.

The modelling system was demonstrated and tested with an indicative case study. The results demonstrate the major advantages of the integrated planning system, which are the simplicity of model structure, and the feasibility of plans developed at the different planning levels. The yield description and outturn optimization system, when used with the outturn control method, provides plans that are feasible, and which can be used to manipulate the quality of log shipments in an easy and flexible manner. This capability has not been evident in planning approaches reported in the literature.

The integrated log merchandising methodology developed in this study can be easily adapted for use with existing planning systems. There is need for further work on the development

of the short term tactical model, in order for the framework to provide fully integrated plans. The method, however, requires further testing and comparison with alternative planning techniques, in order to fully document its potential.

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Chapter 1

Introduction

1.1 Background

A major problem which forest managers face when planning utilization of a resource, is how to merchandise the wood material to best economic advantage. The merchandising problem involves developing a marketing plan for the resource, which is consistent with market demand, the physical, spatial, and temporal characteristics of the resource, and the short and long term goals of the organization. The decisions required in developing such a plan comprise when and how stands in the resource should be harvested, how stems in the stands should be converted into logs, and the utilization processes or markets to which the material should be allocated.

The merchandising decisions made for a resource affect not only the conversion efficiency of downstream processing, but also have significant impacts on the economic realization from the resource, the development of log markets, and on regeneration of the next crop. For this reason, a lot of attention has been directed at developing models to assist managers in making these decisions, with marked opportunity benefits. Examples of the size of such benefits include: a 20 % gain in financial value of logs achieved by adopting better log bucking methods alone (Pnevmaticos and Mann, 1972); annual opportunity savings of over US \$ 200,000 from better harvest planning for a resource (Hay and Dahl, 1984), and; opportunity savings of over US \$ 100 million realized over a seven year period from using bucking simulators in training workers on improved bucking practices (Lembersky and Chi, 1986).

Such models have also been put to diverse uses, apart from just planning of log merchandising. Examples include: analyses of the implications of proposed forest land investments (Barros and Weintraub, 1982); for forest valuation (Papps and Manley, 1992); in evaluation of timber sale bids (Olsen, Pilkerton, Garland and Sessions, 1990); and for assessing potential outturn by log assortments from a resource (Deadman and Goulding, 1979; Eng, Daellenbach and Whyte, 1986); in mill production planning (Mendoza and Bare, 1986; Maness and Adams, 1991; Sicad, 1993; Reinders, 1993); and, for resolving legal resource use and management conflicts (Kent, Bare, Field and Bradley, 1991). In addition to the relatively few examples in the published literature, Gunn (1991) observes that there is an extensive use of models in forestry organizations worldwide, although only a few of these appear in the published literature.

However, with respect to log merchandising most of the research has focused on either harvest scheduling or single period log allocation, and models that address multiple period log production are not evident in the literature. Most of the applications in the published literature are not solved in an integrated manner, but are instead solved for single time periods, for single stands, or do not address the full range of merchandising decisions required for planning at operational and longer term levels. The consequence of this is that it is not possible to develop strategies that are optimal for whole forest estates for time horizons that encompass both short and longer term objectives, or to perform an evaluation of trade-offs between merchandising strategies in different stands, and between different temporal levels of decision making.

This study attempts to address these shortcomings by focusing on the development of a decision support methodology for integrated long and short term planning of log merchandising. Such an application requires the coordinated modelling of whole forest estates, and must also encompass the various temporal decision making levels. The results of the study are presented and discussed in succeeding chapters of this study. The rationale for the study are discussed in this chapter and the next one, and the first part of this chapter describes the context within which log merchandising decisions are made, and also highlights the need for greater integration of log merchandising decision making. The objectives of the study are then presented in section 1.3, and the scope of the study are presented in the last section of the chapter.

1.2 Statement of the problem

The total volume of different log quality classes within a resource can be altered in the long run only, for instance through new planting, or adoption of alternative silvicultural and management regimes. But, the gains from such strategies can be realized only after a considerable time lag. However, since a given log quality class can be supplied to diverse markets which require similar or lower stem quality features, a manager has some opportunity for altering the log mix supplied to the markets in the short term. Because of this, forest production has been described as involving variable output proportion in both the short and long run (Greber and Wisdom, 1985). The former refers to the proportions of the various quality classes within the resource, which can be altered only in the long run, and the latter to the marketing mix of log types from stands, which can be altered with some flexibility in the short run. Log production, therefore, has a joint product nature, as a result of the complementarity and possibilities for product substitution that exist between the different log grades. This is because the supply of one log quality class in a period depends partly on the demand and prices of the other grades that can be supplied from the same resource.

In times of increasing log demand and prices, the manager of a resource which has limited material above minimum age of harvesting, therefore, has three possible avenues for capitalizing on the favourable market environment. The first is to exploit the joint nature of log production within a stand by supplying log assortments with higher values at the expense of the rest. The other approach is to trade-off values of the various stands, for instance by lowering the minimum age of harvesting for certain stands, or a combination of the two. While the use of the former approach has been more apparent, for instance through downgrading (see Greber and Wisdom (1985) and Manley and Threadgill (1986a)), evidence that the second avenue has also been used as a means of maximizing short term financial opportunities also exist. In New Zealand, this is evident from the fact that the average age of clearfelling for radiata pine plantations has declined from between 30–40 years only a few years ago, to between 25–28 years today. This trend is partly accounted for by, and has become more pronounced as a result of the recent dramatic upturn in export log prices (Park, 1993). It is likely though, that the latter approach, which involves a combination of the two earlier ones, is likely to be most common.

A factor that complicates log merchandising decision making in a market driven environment, is potential conflict in objectives between short and long term planning. The major

objective of short term planning is frequently efficient performance within constraints of meeting immediate supply commitments, so that value maximization becomes secondary in importance at this planning level (Reinders, 1993). If the major objective of an enterprise is maximization of returns, then this implies that while short term wood merchandising plans can be market driven, longer term plans should aim to exploit resource driven merchandising strategies, as these often provide the greatest avenue for adding value to the resource. These conflicts in objectives create a dilemma for resource managers: the cutting strategies to employ in each stand and period, that maximizes some prior established utility.

Because the log merchandising decisions made in one period affects the opportunities for merchandising the resource in all subsequent ones, there are several questions that must be asked of any selected strategies. Are they in any way optimal for the entire resource over the whole planning horizon? What effect, if any, do such strategies have on the long term profitability of the organisation? Do such strategies affect the long term opportunities for the firm to maximize value of the resource? To what level do such strategies expose the organization to risks arising from medium and long term fluctuations in demand and prices of the various log classes?

In order for any planning process to provide answers to such questions, therefore, the determination of log production strategies and the scheduling of harvest for the stands in an estate should be evaluated in an integrated way. This would also enable the modelling to be useful for reconciling the conflicting requirements for long term resource driven, and shorter term market driven merchandising strategies. Vertinsky, Brown, Schreier, Thompson and van Kooten (1994) discuss the issue of integration in forest management planning, which, although concerned with integration in a spatial sense, applies equally to the temporal log merchandising one. In that discussion, they observe that "... when regional problems are solved in isolation, the results ignore global measures of production and value, global constraints, and interregional transfers." By substituting 'short-term' for 'regional' in this quotation, this observation becomes just as true for forest planning in the temporal context, as it is in the spatial one.

This study, therefore, was initiated on the rationale that there is a need for development of planning methodologies which managers can use to assist in making log merchandising decisions in an integrated manner. The requirements of such a planning methodology are several, the first of which is that resulting plans must be optimal for the whole forest estate,

and over the entire planning horizon. The second requirement is that the resulting plans must be feasible, to which there are two different aspects. The first is that the long term plans should be implementable as a series of short term plans, which requires feasibility in both a spatial and temporal sense.

The other feasibility issue encompasses the link between planning and control of log output. It is a consequence of the fact that while log merchandising plans are developed at the logging setting, stand, or forest levels and therefore involve multiple stem considerations, the implementation during harvest is a tree specific, single stem process. As a consequence, there is a danger that the detailed output targets in the merchandising plans may not be realizable as a series of single stem decisions made during execution. Any integrated modelling system used in generating such plans should be capable of addressing this problem. Other requirements of such systems are that they should be simple, to enable use by non specialist managers, and that they should be capable of providing solutions in a practically reasonable time when used for problems of realistic sizes.

1.3 Objectives of the study

On the basis of the foregoing, this study was formulated with the specific objectives below.

1. To develop a methodology for yield description that enables the evaluation of trade-offs between medium term harvest schedules, short term log production and allocation plans, and operational log production and allocation schedules.
2. To develop a framework and methodology for integrated planning of the various log merchandising decision levels, which include medium and short term harvest scheduling and log production planning, and operational log production and allocation.

The methodology should have the capability to be useful for evaluating the trade-offs in objective (1) above. Other desirable characteristics of the methodology are the following :

- it should be robust, and capable of being used in developing feasible plans for diverse log grades;

- it should allow flexibility in changing log mix production plans in response to a dynamic marketing environment, without requiring extensive further data collection fieldwork;
 - it should not require prohibitive computer resources to solve when used for problems of a realistic size.
3. To demonstrate how the planning framework and models can be used for modelling the multiple period log merchandising problem with a suitable case study, and to test the feasibility of the resulting plans.

1.4 Scope of the study

The main focus of this study is on the integration of stem conversion considerations, which is an instantaneous, tree specific, single stem decision, to log allocation and harvest scheduling, which might be multiple time period processes, but involve multiple stem considerations and decisions. This problem is explored with respect to forestry systems that Allison (1992) described as Intensively Managed Plantations For Early Harvest (IMPFEH). These are fast growing softwood plantations of species exotic to both New Zealand and Kenya, the management of which is similar in many ways to other crop production systems. Log merchandising planning requirements for uneven aged, naturally regenerated, and other such forests planning situations, which may require other specialized methodologies, are therefore not considered in this thesis.

The problem is considered from the viewpoint of a resource owner who supplies material to markets with disparate requirements by log specifications. Such an enterprise can include integrated firms, but these are therefore assumed to be organized into autonomous profit centres, with the forestry and processing mills operating as separate entities. Under such an environment, internal transfer prices for logs and other materials are assumed to be equivalent to market prices. The focus is explicitly on how the forestry business can best maximize revenues over the short and medium term from supplying material to the markets, and how to meet demand and other wood supply commitments to the maximum extent possible. External purchasing of materials is not considered, nor are issues related to log remanufacturing and options for processing the wood material. It is however recognized that this limited considerations is a simplistic view, and that greater realization of value maximization for integrated forest product firms frequently lie in closer integration

of processing and log merchandising. However, this requires a more extensive treatise, which is outside the scope of this study.

The approach adopted in this study is from the pre-harvest planning perspective, and which eliminates the evaluation of possibilities for remanufacturing of harvested material. The study also assumes the availability of sufficient pre-harvest inventory data to accurately characterize the resource with appropriate analytical tools. Although data requirements for modelling the integrated planning problem are considered from a global perspective, issues related to development and selection of appropriate sampling techniques and intensities and other statistical requirements related to the data collection are not considered.

1.5 Structure of the thesis

In Chapter 2, a review of the use of models and modelling in forestry, and a discussion of the major developments in log merchandising decision support systems that have appeared in the published literature is presented. The discussion focuses on the features and major developments of the various classes of models used in log merchandising decision making, and highlights the perceived gaps in the integration of long and short term planning, and operational scheduling of log production. Chapter 3 documents the development of a framework that is proposed for the integrated modelling of long and short term planning and operational scheduling of log merchandising. The detailed features, including the mathematical structure, of the models within this framework are also presented in that chapter.

A case study was used for demonstrating, testing, and evaluating the proposed planning framework and its constituent models, and this is presented in chapter 4. The application of the planning system and the models to the case study, and the results of the modelling are also presented in that chapter. In Chapter 5, the major issues relating to the proposed modelling framework and models, their development, and the results of application of the system to the case study are discussed, together with implications of using the proposed system. Chapter 6 summarises the major results of the study, and the major conclusions which can be drawn from the development of the modelling system, and its application to the case study are also presented. In the last chapter, some suggestions for future work,

arising from developments in this thesis and some remarks regarding its possible adoption, are presented.

The detailed input data and output of results of the case study in Chapter 4, and details of the *XCut* bucking model and the operational model problem formulator, which were developed as part of this study are presented in the appendix. Appendix A details the mathematical formulation of the *XCut* stem bucking model, and discusses computational issues related to the model, and experiences with its development in the Prolog language. The main part of the second chapter of the appendix, Appendix B.1, is in the form of computer files contained in the diskette that accompanies the thesis. The files contain the detailed input data and output results of the case study, run time versions of the main programs developed in this study, and sample input and output files for the programs. The details of the files and how they can be retrieved is described in that appendix.

Chapter 2

Review of Literature

2.1 Models and modelling in forestry

A model can be defined as a mathematical or logical relationship which obeys specified conditions, the behaviour of which is used to understand a system. A system, on the other hand, is a collection of interacting components which act together to achieve a common goal. Neelamkavil (1987) describes the major purposes of modelling as being to aid in the understanding, design, operation, prediction, and control of a real system, through the study of simple abstractions of the system. Planning models are therefore logical or mathematical relationships that are used as decision making aids, and such models may range in complexity from the toss of a coin to sophisticated computer based models (Johnson, 1989).

Forest production is a complex biological and physical system whose final product, most commonly wood fibre, is the result of intricate interactions between the environment, quality of the stock, and management interventions over time. The quantity and quality of the stream of products from a forestry system over time are determined, to no small extent, by the nature of management interventions, and the timing of such interventions with respect to the age of the crop. Forest production is characterized by long gestation periods and an infinitely large combination of management actions that can be applied to the forest over such horizons, which make it extremely difficult and complex to predict the results of any interventions. As a result of this, forestry has a long history of using models for planning and scheduling regeneration, management and harvesting interventions,

and for predicting growth and yield responses to these and other growing conditions.

Earliest models in forest management were developed to aid in regulating forests so as to maintain an even flow of forest products, as a result of anticipated crisis in wood supply. Today, the scope and objectives of forest management decision support models are very disparate, ranging from early models for determining optimal rotation (such as that of Faustman (1849), cited in Gunn and Rai (1987) and Whyte (1988)), scheduling of harvests, management interventions, and regeneration (Pearse and Sydneysmith, 1966; Johnson and Scheurman, 1977; Johnson, Stuart and Crim, 1986; Reed and Errico, 1986; Gunn and Rai, 1987; Garcia, 1990), log allocation (for instance, Pearse and Sydneysmith (1966), Eng et al. (1986), and McGuigan (1992)), optimal replacement of equipment (for instance, Ogwen (1988)), forecasting of growth and yield (for instance Temu (1992) and Goulding (1986), to regional, national, international, and global trade sectoral models (such as those reported by Johnson and Whyte (1993), Kallio, Propoi and Seppala (1986), and Dykstra and Kallio (1986)). A hierarchical organization of forest planning and management models, which shows the linkages and inter-relationships between different elements of forest planning and managements systems from Whyte (1991) is shown in Figure 2.1.

Forest growth and production forecasting systems are used for predicting future supply capabilities of a resource, which is an essential prerequisite for regulation. Growth and yield models are concerned with forecasting tree and stand growth and yield responses to site factors and of management interventions. Growth and yield models can be classified into those developed either for natural or plantation forests (Clutter, Fortson, Pienaar, Brister and Bailey, 1963). Each of these classes can be further subdivided into those for predicting stand and tree growth (Munro, 1974), depending on whether they are formulated for forecasting growth of stands or of individual trees.

The most important components of growth and yield usually modelled at the stand and tree levels include volume, height, diameter, and mortality over time. Growth predictions are necessary components for production forecasting tools, such as bucking models at the tree level, and for harvest scheduling and other yield regulation systems at the forest and stand levels. Temu (1992) provides an extensive discussion of growth and yield models, their development and uses, while (Goulding, 1986) reviews growth and yield models for radiata pine in New Zealand.

Production forecasting models, on the other hand, are concerned with determining potential output as a function of possible utilization options. Such models act as the interface

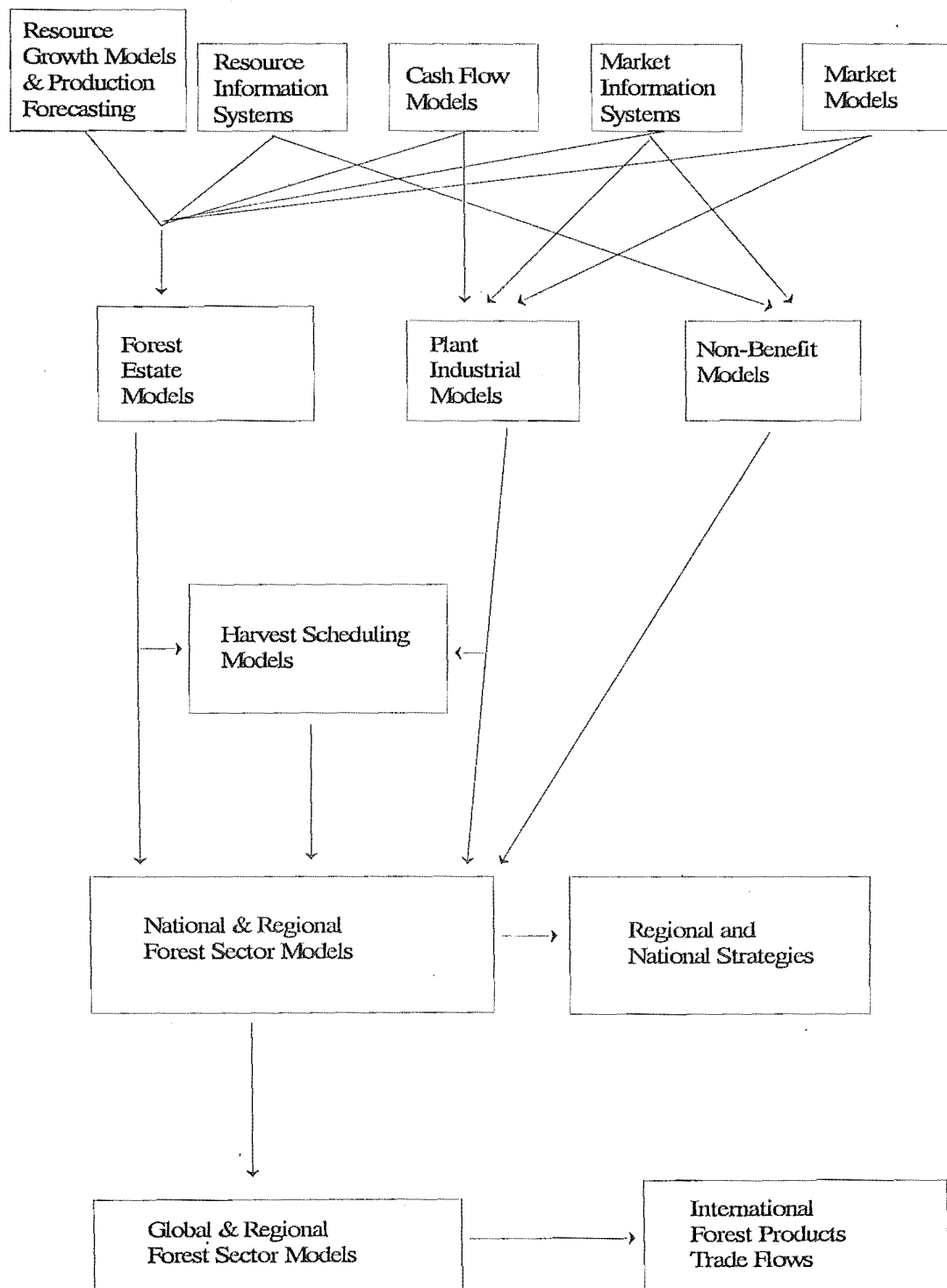


Figure 2.1: Elements and Linkages in Generalised Forest Planning and Management Systems (from Whyte, 1991).

between production and utilization, and incorporate consideration of both characteristics and production capabilities of the resource, and demand requirements of the utilization sector by detailed log specifications. These models frequently utilize growth models for predicting future supply capabilities of a resource.

Forest estate models are concerned with the production of whole forests, which are aggregates of diverse stands. They are used to evaluate medium and long term management strategies which maximize some utility to the owner, usually wood flow or present net worth (PNW), as constrained by prevailing and forecasted market scenarios. Allison (1986) and Garcia (1986a) provide an overview of forest estate modelling in New Zealand, and also describe the major model types and their features as used for this purpose. Forest Estate models are discussed in greater details in section 2.2.1.

Plant industrial models can be divided into single and integrated plant models, according to the classification of Johnson (1989) and Whyte (1991). Single plant industrial models are used to aid in decision making for specific production processes, such as a sawmilling or a plywood operation. Most reported applications of single plant models are based on simulation techniques, such as the work of Sampson (1979), Ward (1986), van Wyk (1986), Park (1986), and Garcia (1986b). The reason for the predominance of simulators in such applications is because LP models have traditionally failed to satisfactorily address the variable factors of production, such as the random nature of log inputs or the unpredictable nature of machinery downtime. Optimization models also do not represent supply buffers and process bottlenecks very readily (Sampson, 1979; Whyte, 1991; Maness, 1989). However, there has recently been an increase in the application of LP models in single plants models, mainly because of the greater efficiency of LP in resolving resource allocation issues inherent in process selection, as compared to simulators. Such LP applications include the work of Mendoza and Bare (1986), Maness and Adams (1991), Reinders (1993), and Sicad (1993).

Integrated industrial models, on the other hand, are used to aid in decision making related to log procurement from multiple sources, allocation of the material to diverse production processes within or outside of the organization, utilization of intermediate products, and the selection of product mixes within each process. Such models include the work of Barros and Weintraub (1982), Gunn and Rai (1987), Pearse and Sydneysmith (1966), Hay and Dahl (1984), van Wyk (1983), and McGuigan (1992). In most such models, the processing is frequently formulated as aggregations of single mill models which are solved

individually (Whyte, 1991). However, because the sum of separate mill plans may not be globally optimal, the need for greater integration of single and integrated mill models has been recognized, and development of such applications has been attempted by Barros and Weintraub (1982), Gunn and Rai (1987), and McGuigan (1992). In these applications, the processing side is considered in aggregated form, and investigations into the implications of integrated modelling approaches which incorporate more detailed formulation of both components is not evident in the literature.

Regional, national, and global and international forest sector models are concerned with long range strategic development of production, consumption, and trade of forest products and related externalities at the regional, national, global and international levels. Examples include the work of Johnson and Whyte (1993) and Broad (1985) at the regional level, Whyte and Baird (1983), and Kallio et al. (1986) at the national level, and Dykstra and Kallio (1986) at the global and international levels. These models are based on a variety of techniques, such as dynamic simulation, mathematical programming, systems dynamics and optimal control theory, and econometric spatial equilibrium models (Whyte, 1991), with most of the systems employing a combination of techniques. Whyte (1991) discusses sectoral models in detail, and describes the required features of such models, the shortcomings of current approaches to sectoral modelling, and implications of these for the future.

Integrated industrial, log production, and forest estate models are principal components of medium and short-term log merchandising systems, and are discussed in greater detail in the next section of this chapter. All the other model categories, although they may significantly affect log merchandising decisions, are outside the scope of this thesis, and are not considered any further in succeeding discussions.

2.2 Past work in modelling log merchandising

Figure 2.2 shows a representation of the log merchandising problem, which can be described as one of developing a log mix production plan for each stand in every period of an horizon, that maximizes some utility to the owner. Such plans must take into consideration the short and long term demand by log assortments, the characteristics of stems

within each stand and potential changes in these as a result of accretion, and the opportunities for maximizing the value of stems in each stand in both the short and long term. Because such plans must be made for a standing resource, the planning is commonly made from data collected from some form of inventory, either a mid rotation or pre-harvest one for each stand. A crucial role, then, in such a scheme is that of the harvest scheduling, log allocation, outturn prediction, outturn optimization, and outturn control systems.

For the purposes of this discussion, wood merchandising decision models in the literature can be classified into the categories below, on the basis of the aspects of the log merchandising problem that they are formulated to address.

1. Wood supply strategy or forest estate models, which can be further subdivided into:
 - long term, strategic wood supply models, and;
 - medium term, tactical harvest scheduling models
2. Multiple stem bucking or log allocation models, which tend to be single period models, and;
3. Single stem bucking or log production models.

In the hierarchy of forest planning and management systems of Whyte (1991) discussed above and shown in Figure 2.1, these correspond to forest estate models, integrated industrial models, and log bucking or production forecasting models respectively.

2.2.1 Forest estate models

Early forest management was concerned primarily with providing a sustained supply of wood and other products, which focus evolved mainly as a response to anticipated crisis in wood supply. Early aims of forest management and models developed for this purpose, such as the work of Faustman (1849) (cited in Gunn and Rai (1987); Whyte (1991), Dykstra (1990), and Tait (1987)) were, therefore, mainly concerned with regulating forests as a means of guaranteeing supply of a sustained even flow of wood and other products from forests. Gunn and Rai (1987) refer to this class of models as simple dynamic models,

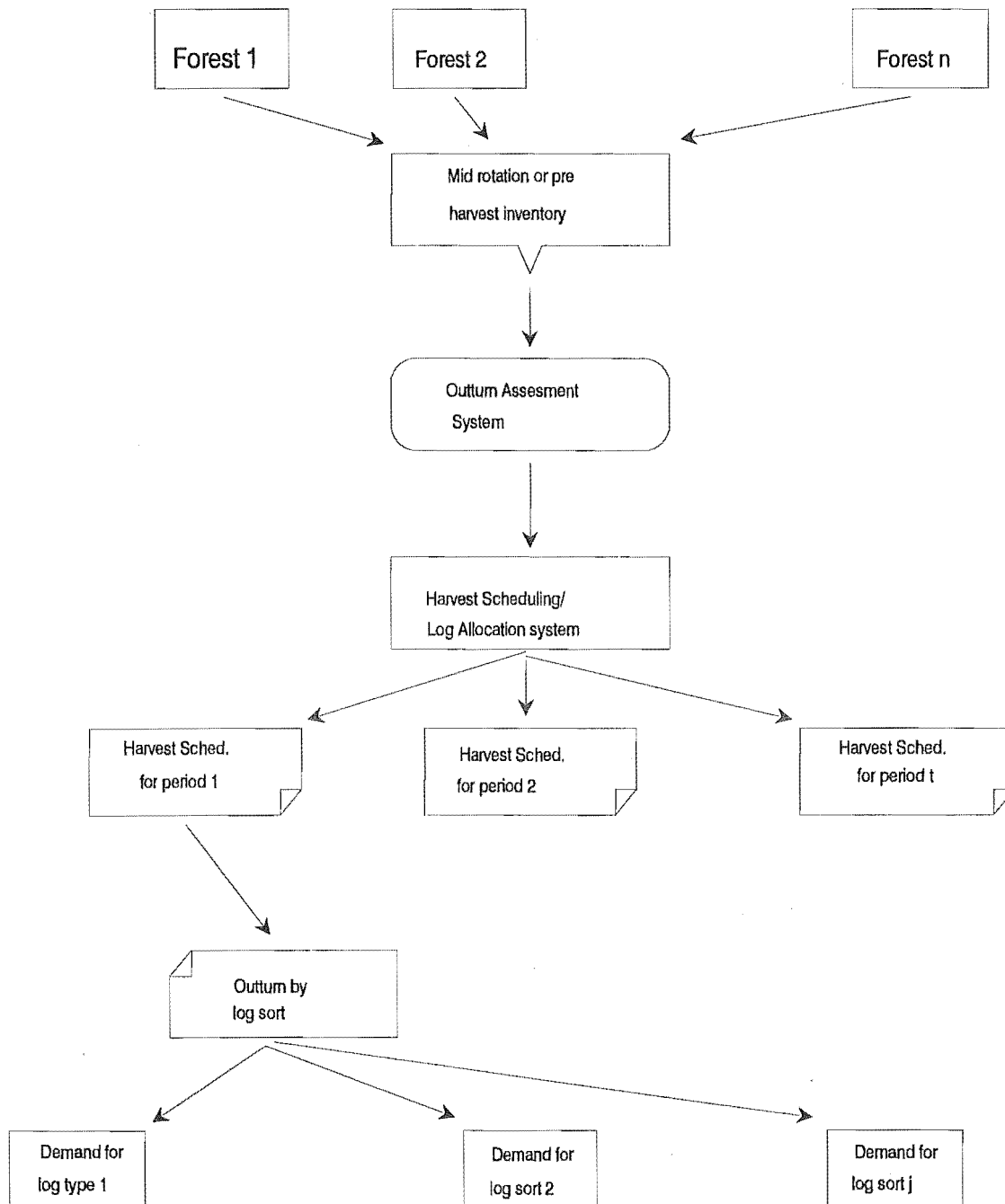


Figure 2.2: The log merchandising problem

because they are formulated for determining a rotation that maximizes production or return from a specific area of land in perpetuity, but do not consider the detailed needs of the wood consuming sector. This is not only because no constraints are imposed on volume production in the models, but also because such production is not disaggregated into log assortments (Gunn and Rai, 1987; Whyte, 1991), which factor is crucial for planning utilization and processing.

With suitable yield predictions, optimal management strategies for each stand within an estate can be fairly easily determined by the method of modelling production on a unit area with simple dynamic models. This is especially the case if maximum total volume production or returns is the variable of interest, with little consideration given to the utilization sector. However, most forestry enterprises have constraints on production, and are also concerned with not just total volumes or revenues, but also with its composition by log assortments, and its timing and regularity.

Due to the often random distribution of age classes within a forest and the requirements of the wood utilizing sector by log assortments, extending stand prescriptions from simple dynamic models to the whole estate are, therefore, unlikely to yield optimal results; for instance, see de Kluyver, Daellenbach and Whyte (1980). This is because the streams of inputs and outputs from the estate are likely to fluctuate widely, following the age structure of the estate, which is undesirable from a utilization perspective. The other disadvantage is that such models do not provide managers with any mechanism for constraining production as a means of balancing demand and supply to markets. Consequently, forest estate models based on mathematical programming techniques are now the predominant basis for most regeneration and harvest planning systems.

Forest estate models have been described as the modern form of forest working plans, which take advantage of the capacity of computers Allison (1986). Forest estates can be considered as aggregates of forest stands, which can be at the forest, regional, or national levels (Garcia, 1990). In New Zealand, crop types are used as the basic units of estate description. Crop types are defined as areas of trees uniform for practical purposes of description and management (Allison, 1986), and which therefore have the same streams and magnitudes of inputs and outputs. Forest estate modelling techniques are predominantly based on simulation (Garcia, 1981; Allison, 1986; Allison, 1992; Elwood and Rose, 1990; Jamnick, 1990), and linear programming (LP) and related methods (Johnson and Scheurman, 1977; Barros and Weintraub, 1982; Gunn and Rai, 1987; Garcia, 1984; Garcia,

1990; Laroze and Greber, 1991; Kent et al., 1991), (Papps and Manley, 1992; Ghandforoush and Greber, 1986), although models based on Dynamic Programming (DP) and Markov Chains (Lembersky and Johnson, 1975; Chen, Rose and Leary, 1980), and Artificial Intelligence (AI) methods (Koten, Herrington, Chambers and Davis, 1991) have also appeared in the literature.

Approaches based on DP and markov chains, such as those reported by Lembersky and Johnson (1975) and Chen et al. (1980), can be classified in the category of simple dynamic models, as they are formulated to develop management regimes which maximize revenue or volume production over a unit area of land. DP and Markov Chains have not found much favour in forest estate modelling for two other reasons, in addition to those already mentioned above for simple dynamic models. The first is that with the technique, problem sizes become prohibitively large and difficult to solve when formulated for problems of a realistic size, which commonly involve a multitude of stands and products. Another limiting consideration is the fact that there are no general purpose solvers for use with the technique, but instead, specialised code are required for each application. However, DP modelling approaches that consider inputs and outputs for whole estates have recently appeared in the literature (Gong, 1992), but the problem of solution techniques is still likely to limit their use.

Neelamkavil (1987) describes simulation models as being a class of systems which are not amenable to solution by conventional numeric or analytical techniques. Simulation involves duplicating the dynamic behaviour of a system, by substituting its properties with those of another system which is to be simulated (Daellenbach, George and McNickle, 1984). The properties of the system are commonly described by an abstract mathematical model, which is used to analyze how the system responds to specific factors. The factors are represented in the form of inputs to the system, which results in a stream of output responses, and such models are therefore essentially *input-output* models (Daellenbach et al., 1984). In forest planning, examples of forest estate models based on simulation techniques include IFS (Interactive Forest Simulator) (Garcia, 1981), RMS2020 (Resource Maturity Simulator 2020) (Allison, 1992), a model reported by Elwood and Rose (1990), and FORMAN (Jamnick, 1990).

In simulation models, the state of a forest is described by the area in each age class in every crop type. In any period, some of the area can be harvested, regenerated, or otherwise

treated. The state of the forest in any future period is then a function of the state of the forest in a previous period, and the treatment effected on it between the two periods. Using a simulation model, a manager specifies inputs to the model in terms of treatments, such as levels of cuts or plantings. These results in a stream of outputs, such as volumes by log assortments, a new age structure of the forest following treatment, revenues, costs, etc, which represent consequences of the interventions. The outputs are determined by multiplying the effects of the treatments, and the state of the resource, by values in appropriate tables. Alternative management regimes can be explored by specifying different combinations of treatments in separate model runs, and a desired management plan is then developed from results of the runs.

A major shortcoming of simulation models, however, is that there are potentially a very large combination of management interventions that can be implemented on a stand or estate, of which only a limited number can be evaluated. Simulation techniques are used to develop management strategies by what is essentially a trial and error process. As a consequence, there is no guarantee that superior management alternatives may not have been overlooked. Techniques based on constrained optimization by LP and related approaches are therefore more widespread because of this, and also because of the extensive availability of commercial packages for solving such applications. This is in contrast to simulation models, where both the model representation and solution routines may have to be developed for particular applications.

Nevertheless, both simulation and optimization should be considered as complementary tools, where the consequences of solutions from optimization models can be explored in detail by simulation models (Whyte, 1991). Examples of this are evident in the literature, such as the IFS (Garcia, 1981) and FOLPI (Garcia, 1984) simulation and optimization models which share the same basic input data format and problem representation scheme, and can therefore be used to model a problem in common. Vertinsky et al. (1994) have also recently reported a modelling system which integrates LP and simulation based forest estate models.

Forest estate models based on LP and related techniques, yield solutions through optimization, unlike AI and simulation models. In LP and related techniques, an objective function and a set of constraints on production are specified, which describe the major features of the problem being modelled. The objective function can be, for example, maximization of revenues, minimization of costs, or maximization of volumes. The constraints

can be of several types, such as even flow, non declining yield, capacity constraints on volume production by period, minimum levels of cut, etc. In addition to these are structural constraints, which govern the flow and conservation of area and products between crop types, markets, periods, etc. Once the objective function and constraints have been specified, an optimizer is then used to determine activities for the decision variables that optimize the objective function, while satisfying all of the constraints.

Early use of forest estate models based on LP techniques, like the classical European approaches to yield regulation, were concerned mainly with regulation of forests as a means of providing a sustained yield of timber (for instance, see Clutter et al. (1963), Nautiyal and Pearse (1967), Hoganson and McDill (1993), Dykstra (1984), Davis and Johnson (1986)). The stress on attaining normal forests led to classification of LP approaches to forest regulation into volume and area controls (Dykstra, 1984; Davis and Johnson, 1986), depending on whether regulatory constraints were specified by volume, or area in the different age classes. However, in a utilization-oriented intensively managed short rotation plantation forestry environment, the desirability of forests with normal age distributions is questionable, and the time that would be required to convert such forest estates to one with normal age distributions is likely to be so long as to make such targets unattainable (Garcia, 1986a). As a result, this categorization is rarely used in intensively managed plantations.

Today, the stress is on the efficient management of estates with irregular age distributions, under the constraints of utilization and markets. For such purposes, two basic forms of harvest scheduling model formulations based on LP have been recognized in the literature: the model I and II formulations of Johnson and Scheurman (1977). The main difference between the two model forms is in the definition of what constitutes activities within the models, and the implications of this with respect to whether a stand's identity is preserved or lost after a regeneration harvest.

In Model I, an activity refers to a complete set of management prescription over a specific land area for the entire planning horizon. In model II, in contrast, an activity refers to a complete set of management prescriptions over a land area from the time it is regenerated, until it is regeneration harvested. The identity of a stand is therefore not preserved after a regeneration harvest in model II, as the land area can be broken up and merged with other management units after harvest, while stand identity is preserved in model I. This can be considered as a drawback for model II formulations (for instance, see Gunn and

Rai (1987), and Barros and Weintraub (1982)) if it is desired to define management activities by stands and not portions thereof, for which reason Johnson (1989) described model II as being inaccurate. Another drawback which has been cited for both model forms is that they do not adequately provide a flexible means of mixing silvicultural options and management regimes, which is a desirable attribute of systems for modelling intensively managed short rotation plantation forestry (Whyte, 1991).

A third model form, which is an algebraic representation of a network model, has recently been described by Garcia (1990). Applications of the formulation have been reported by Garcia (1984), Reed and Errico (1986), Gunn and Rai (1987), and Davis and Martell (1993), and have been used by forest managers for many years in manual planning procedures. This model form is also the one which underlies many simulation models, such as RMS2020 (Allison, 1992) and IFS (Garcia, 1981) discussed above, which formulation is examined in greater detail in section 3.4.3. This formulation overcomes the limitations of model II by allowing identity of stands to be kept, while providing greater flexibility in the modelling of management prescriptions than either of the two formulations. However, Garcia (1990) argues that all three model forms are substantially equally versatile in their ability to model planning problems, although there is a trade-off between increased flexibility and model size.

From a computational perspective, model II leads to a larger number constraints than model I, while model I formulations tend to have a larger number of variables. Since computation time of LP problems commonly increases with the number of constraints in a model as a rule of thumb, model II is likely to result in greater computation time than model I when used for similar problems. However, Garcia (1990) observes that modern large scale solvers are very efficient at exploiting model sparsity. As the smaller number of constraints in a model I formulation is achieved at the expense of increased density of the matrix, the advantage of a smaller constraint space in model I may not be as significant as it first appears. Garcia (1990) discusses various solution strategies that can be used to exploit the features of the various model forms as a means of improving model solution time. It should be recognized, though, that only a limited number of constraints and activities can be incorporated in any LP model, and such models may, therefore, not fully represent features of the corresponding problem.

In all these forest estate model formulations, strategic management prescriptions are commonly specified by broad aggregated resource classes (aggregates of crop types and log

product classes). In tactical planning, management prescriptions may be disaggregated down to the stand level, but wood supply projections are commonly still made by broad end use classes. Only in a few applications such as those reported by Barros and Weintraub (1982), Greber and Wisdom (1985), Gunn and Rai (1987), and Papps and Manley (1992), are issues of complementarity and substitution between log product classes modelled, but these are done by aggregated log quality classes. In the studies, the feasibility of the log production plans are also not addressed. It is therefore unclear if the targets in such plans can be realized as a series of short term conversion decisions made at the single stem level. As a consequence, there is no mechanism for evaluating trade-offs between log production mixes and timing of harvest in a flexible and feasible way. On their own, therefore, forest estate models, while suitable for planning long term harvesting issues, do not provide the level of sensitivity and flexibility required for the detailed log production planning at the medium and shorter term levels, that is required in this study.

2.2.2 Log production and allocation models

Log bucking is the crosscutting of stems into logs assortments, and is the first log merchandising decision made. The primary stem conversion decision is frequently the most important one, not only because of its effect on revenues, but also because it affects the efficiency and flexibility of downstream processing. For instance, Murphy and Twaddle (1986) estimated that up to 22 % of the value of a stem can be lost at the log making stage. For this reason, a lot of attention has been directed at developing models to assist in improving of log bucking decisions. Early log bucking decision aids were in the form of rules printed on cards, which were supplied to fellers (Maness, 1989). With the advent of powerful and accessible computer systems, these were quickly superseded by computer based models, which provided better, tree specific solutions.

The earliest reported log bucking model was based on linear programming (Smith and Harrel, 1961), which involved specifying a few alternative strategies for each stem class, and the decision variables in the model were then the number of stems within a class to buck with each strategy. The disadvantages of this approach are twofold. The first is that the bucking strategies for the stems must be known in advance, but this is a solution which should be provided by such a decision making aid. The second one is that there are potentially a very large number of bucking strategies for each stem, of which only a few can be included in the model. As a result, the method is likely to yield sub-optimal results,

and LP has therefore found little favour as a technique for solving single stem bucking problems.

The most commonly used analytical technique in bucking optimization today is dynamic programming (DP) based on the formulation first described by Pnevmticos and Mann (1972), which itself is an adaptation of the one dimensional knapsack formulation of Gilmore and Gomory (1961). This formulation has since been implemented widely, with modifications, for instance by Lembersky and Chi (1986), Eng et al. (1986), Deadman and Goulding (1979), Threadgill (1987), Faaland and Briggs (1984), and Maness and Adams (1991), although models based on arc networks (Sessions, Layton and Guangda, 1989) and branch and bound approaches (Bobrowski, 1990; Bobrowski, 1994) have also been tried. The arc network approach is closely related to the dynamic programming one, and yields comparable solutions. Branch and bound approaches have the drawback that an upper bound on stem value is required at every node, but this cannot be known until an optimal strategy for the whole stem has been determined.

Models based on DP are therefore likely to remain more popular, despite the high demands on computer time that the technique requires. It is conceivable, however, that satisfying solutions can be obtained from heuristic formulations based on decision rules which can solve the bucking problem much faster than DP, however this has not been tried to date. Nevertheless, this drawback is increasingly becoming redundant, with the advent of more powerful yet cheaper computers.

In single stem bucking models, the decision is driven only by the value of the different log types, and is constrained only by the unique form and profile of each stem, and the specified quality requirements of the feasible log types. No consideration is given to market demand for the various log assortments in the bucking evaluation. As a result, solutions are optimal only for unique stems, and are rarely optimal for a whole stand or forest. They are used, therefore, mainly for assessing optimal conversion strategies for specific stems, and for determining the maximum outturn obtainable from a resource. By themselves, therefore, this class of models is not suitable for log production planning.

Log production or allocation models are used to determine optimal distribution strategies for log assortments to disparate markets and utilization processes. Most log allocation models are formulated as linear programs, and follow the pioneering work of Pearse and Sydneysmith (1966). Log allocation models can be discussed in three categories, depending on the formulation and decisions addressed. These are stand alone log allocation

models; integrated systems of stem bucking and log allocation models; and, those which integrate log allocation, stem bucking, and processing of logs into end products.

Examples of the first type of model include those reported by Pearse and Sydneysmith (1966), van Wyk (1983), Hay and Dahl (1984), and McGuigan (1992). In these models, the log allocation decision is constrained by market demand and the availability of the various log assortments. Consequently, it is, therefore, usually assumed that yields by log assortment are known, and bucking decisions for all stems in a stand precede the allocation one. An undesirable consequence of this is that a satisfactory balance between demand and supply by log assortment may not always be achieved. This is despite the fact that alternative strategies which could yield higher returns from the allocation one can potentially be developed. Approaches which integrate the optimization of stem bucking and log allocation decisions is an attempt to overcome this limitation.

The integration of stem bucking and log allocation is usually formulated as LP decomposition, and solved by delayed column generation, a technique which was developed for solving knapsack problems of two or more dimensions (Gilmore and Gomory, 1963). In this application, the problem is formulated as a two dimensional knapsack problem, in a two stage approach in which a DP stem bucking model is interfaced to an LP log allocation model. The DP model develops non-dominated bucking strategies, which are passed to the LP log allocation model. On the basis of the shadow prices for the various log types from the LP, new, more profitable strategies are then developed by the bucking model for optimization by the LP. The process stops when there are no new strategies that can be generated by the bucking model, which improves the objective value of the LP. Examples of the use of this approach include those reported by Faaland and Briggs (1984), Eng et al. (1986), Mendoza and Bare (1986), Maness and Adams (1991), and Reinders (1993).

This approach leads to better balancing of supply and demand by log sorts, but has the disadvantage that it requires substantially long solution times for single period problems of a realistic size. This can make such models impractical to solve for multiple period problems because new columns have to be developed for each stand in every period of an horizon at each iteration. The generation of columns by a bucking model is likely to be the limiting phase in this regard.

The method has been extended to include the decision on how to convert log assortments into boards or lumber. This development is a cognizance of the fact that the value of a log, especially in an integrated forest products firm, lies not only on its market value, but

also on the value of the lumber which can potentially be produced from it. This extension is achieved by modelling the conversion of logs into lumber as a third dimension of the knapsack problem. It is formulated as a DP model for determining the mix of lumber to produce from each log class that maximizes the value of a log. As a result, the value of a log assortment to the objective function of the LP reflects not only its market value, but also that of the lumber which can be produced from it. Examples of this extension include the work of Faaland and Briggs (1984), Mendoza and Bare (1986), Maness and Adams (1991), and Reinders (1993). The extension of the planning methodology to log processing while is of interest as a means of determining a more accurate value for logs, is, however, not in the scope of this study.

2.2.3 Pre-harvest planning of log mix production

The planning of log mixes to produce from each stand during harvesting is usually based on analysis of pre-harvest or other inventory data for the stands. The intention of such analyses is to determine the log mixes which can potentially be produced from the stands which maximizes some utility. This evaluation is the function of an outturn assessment system, to which there are four different approaches evident in the literature. Most of the methods are based on the same general technique, which involves evaluating potentially optimal conversion of stem samples from inventory data, into feasible log assortments. The log mixes determined for each stand in this manner is then projected to total stand yield, on the basis of the proportion of the total area of a stand covered by the sample plots. The four approaches are:

1. heuristic methods which use search routines to determine strategies yielding satisfactory log mixes for each stand;
2. those in which outturn is determined directly to market log grades with a bucking model;
3. those in which several feasible strategies are defined, and the best one is selected by a log allocation model, and;
4. integrated systems of log bucking and allocation models, which employ column generation techniques.

The first group of models include the work of Sessions, Olsen and Garland (1989) and Murphy (1993b) (cited in Goulding (1993)). In Sessions, Olsen and Garland (1989), the log mixes are determined by an iterative process, which involves heuristically adjusting log values and then performing a bucking evaluation at each iteration. The process is continued until a set of values is obtained that yields volumes or proportion of the total volume from a stand in specified log types or lengths. The approach of Murphy (1993b) is similar to this, but differs in employing the search strategy of Hooke and Jeeves (1961), and also in the fact that not only log values are modified at each iteration, but also some other log specification variables, such as Small End Diameter (SED).

Heuristic approaches have several limitations, the most obvious of which is that they can be applied only on a stand by stand basis, and cannot provide a solution that is optimal for an entire estate.

A second problem with the method, and which is related to the first, is that there is a likelihood of sub-optimization if a global plan is formulated as a sum of separate plans for each stand. This is because the demand constraints are imposed at the stem and stand levels, and supply capabilities of the other stands are not considered in the decision (for instance see de Kluyver et al. (1980) on the effects of developing estate models as a sum of separate plans developed for each stand). A third problem is the potentially high computational requirements of the approach. Goulding (1993) reports that a sample problem for a single stand with two demand constraints was solved in 5–6 iterations. However, the same problem required 35 iterations when just two additional constraints were imposed. The computation time, therefore, appears to increase by orders of magnitude to the number of constraints, and is likely to be prohibitively expensive to solve for realistic problems. This is because such problems commonly involve a multitude of stands and time periods, and are likely to require a much larger number of production constraints.

The second approach is widely used in New Zealand with the MARVL pre-harvest inventory system (Deadman and Goulding, 1979). In this method, a list of log specifications is developed, which provides a description of the required log types by value and physical specifications (stem quality features, minimum and maximum small and large end diameters, minimum and maximum lengths, etc). A bucking evaluation is then performed to determine the log mixes to be produced from each stand, that maximizes stand value. In the approach, the product preferences of the manager are specified to the bucking model through log values, which drive the optimization. Stand value is therefore maximized by

optimizing the value of individual stems, and a log allocation model is then used to determine the optimal distribution of the material generated in this way.

Apart from the much lower computational requirements of the method, all the other disadvantages of the heuristic approaches applies to this method. Other disadvantages of the method are that the log mix derived in this way pre-empt, and unnecessarily constrains the log allocation decision, and limits the generation of feasible non dominated strategies at the global level. This is because such plans can only be optimal under a limited set of conditions. The first is if the log mix exactly balances demand by log assortments, which is an unlikely eventuality. The second is if the demand for all log assortments are so high that any supply from the estate is insignificant compared to the level of demand. The last is if the organization does not have any supply commitments or are unconcerned with developing and maintaining captive log markets, or other such constraints on production, and can therefore supply any log mixes it desires. Such assumptions are unlikely to hold in most operating conditions, as a consequence of which an acceptable balance between demand and supply by log assortments is not always achieved, as the outturn assessment is not constrained by market demand.

A variation of this method which has been used to overcome some of the limitations, is to develop a limited number of alternative strategies; a secondary function of the log allocation model is then to select the strategy to use for different log quality and size classes (Hay and Dahl, 1984; Smith and Harrel, 1961). Although this constitutes an improvement in the choice of log mixes available to the log allocation model, it still suffers from the same pitfalls. This results from the fact that there is potentially a very large number of bucking strategies, of which only a few can be modelled in the log allocation system for practical reasons. As it cannot be guaranteed that the optimum strategy is among the limited number selected, it also unnecessarily constrains the allocation decision.

To overcome these shortcomings, LP decomposition and delayed column generation techniques have been applied to the problem, which method integrates determination of outturn with the log allocation decision. In this regard, there is need to distinguish between models intended for use in pre-harvest planning, and those for use in processing log yards for making log remanufacturing decisions. This is because the material at a mill yard would previously have undergone a primary grading and conversion process, and the required bucking decision need only consider the length of logs to remanufacture from available material. The processing log yard remanufacturing models include the work

of Faaland and Briggs (1984), Mendoza and Bare (1986), Maness and Adams (1991), and Reinders (1993). The mill yard applications are computationally less demanding to solve than pre-harvest applications, not only because of the simpler choice of bucking decisions, but also because such material will usually have undergone prior grading, unlike at pre-harvest planning. Secondary log bucking models perform a function which, clearly, is not one of outturn assessment, and are not examined in any further detail in this study.

The decision at the pre-harvest stage is more complicated than the log remanufacturing one. This is because the primary conversion decision involves, not only considering length requirements, but it also performs a qualitative grading function, in terms of determining how the distribution of features along a stem affect the conversion decision. The only pre-harvest planning application of the delayed column generation technique in the published literature, is that reported by Eng et al. (1986). That application, which is a single period one, overcomes the major limitations of the other approaches by enabling the generation of plans which are globally optimal, while also providing feasibility at the tree and stand levels. The method, however, has high computation demands, and extending this formulation to provide multiple period plans is likely to yield models which maybe too large and complex to solve efficiently for practical use. Although the increasing availability of cheaper, more powerful computers will make the solution of such models in less time a reality, as yet the computation demands y are still likely to be quite large for practical applications.

There is therefore a need for developing a methodology that enables the evaluation of optimal log production strategies for stands in a feasible and flexible manner. Such an application must be capable for multiple period planning, which can be used for integrated planning of short term log allocation and medium term harvest scheduling. The log production targets developed in such plans must be feasible, and should, therefore, be realisable as a sum of implementations at the single stem level.

2.2.4 Integration of short and long term planning

A crucial requirement of an integrated log merchandising system is the coordination of decision making at the various temporal levels. The main objective of such integration is to ensure that the plans made at the different levels are feasible, and that long terms plans can be feasibly implemented as a series of short term plans; to ensure that short

term plans are constrained by, and are made in consideration of the longer term opportunities for marketing the resource; and to ensure that the short and longer term plans conform with the short and long term goals of the organization. There are two different approaches to integration of short and long term planning evident in the literature. The first can be described as a monolithic approach, which involves developing a large model that incorporate a consideration of the major issues at each decision level in some way. The second approach is hierarchical planning, which involves developing separate models for each decision level, but that are designed with appropriate linkages to ensure feasibility between the levels.

Large integrated systems which incorporate the modelling of both short and long term levels include work reported by Barros and Weintraub (1982), Greber and Wisdom (1985), Gunn and Rai (1987), Papps and Manley (1992), and McGuigan (1992). A basic feature of such modelling is that the harvest scheduling decision is integrated with a log allocation component, so that both decisions are made simultaneously. The problem with this approach is that such models tend to be large and complex, and are therefore difficult to formulate and solve. Another disadvantage of such systems is that the lower levels are not represented in the sufficient detail that is necessary for operational implementation, and features important to the log allocation decision may not be modelled at all, or the models become prohibitively complex.

A significant development aimed at overcoming some of the limitations of the monolithic approach is to use varying period widths within the horizon, a method first demonstrated by Barros and Weintraub (1982). The method involves modelling earlier periods of an horizon in detail by using shorter period widths, while the latter ones are aggregated into multiple ones, and the resource and product descriptions are also provided in aggregated form, and are less detailed as a consequence. This can reduce the size of such a model substantially. Papps and Manley (1992) discuss the potential of the approach for reducing both model size and solution times, and also examine the implications of such aggregations for planning purposes. However, varying period widths are still unlikely to provide the level of detail required for operational implementation in the earlier periods. This is because the large scale nature of such models commonly make it impossible to model detailed features which are specific to the short term problem.

Hierarchical planning systems are a more recent development in the integration of different levels of decision in forestry (Weintraub, Guitart and Kohn, 1986; Weintraub and

Cholaky, 1991; Gunn, 1991; Laroze and Greber, 1991; Vertinsky et al., 1994; Lappi, Nuutinen and Siitonen, 1994). In systems based on the hierarchical planning paradigm, the various levels are modelled separately, but the whole system is designed with the linkages between the various models in mind, with higher level models forming part of constraints to lower level models. This ensures that short term plans are developed in consideration of longer term objectives. However, most of the applications in the literature address issues of harvest scheduling at aggregated levels, and applications which encompass the full range of detailed log production decisions at both operational scheduling and longer term levels, which is the focus of this study, is not evident in the literature. Forestry applications of hierarchical planning systems are reviewed in greater detail in section 3.1 of the next chapter.

2.3 Summary

There has been extensive research into aspects of the log merchandising problem in the published literature. The research has focused mainly on development of models which support decision making for components of the log merchandising problem, which include log bucking, log allocation or process selection, and harvest scheduling. This has resulted in the development of a variety of modelling techniques, which have found successful and widespread use in forestry organizations worldwide. Such systems have also contributed important gains in adding value to harvested resources through opportunity savings. However, the integration of short and longer term decision levels in pre-harvest planning of log production, which can be used for evaluating trade-offs between merchandising options at these levels, has received relatively little attention in the published literature.

A crucial role in the development of integrated log production plans is played by the outturn planning methodology, on the basis of pre-harvest inventories. This is because it not only defines the bounds on production of the various log assortments for the log allocation system, but it also determines the ease and success with which log production plans can be developed within and across the various stands, and decision making levels.

Methods which have been proposed for outturn assessment in the published literature either do not allow log mix production plans to be developed in a flexible and optimal way (Deadman and Goulding, 1979; Hay and Dahl, 1984; Sessions, Olsen and Garland,

1989; Murphy, 1993b), or are complex and have such high computation time requirements as to be impractical to solve for multiple period problems of realistic sizes (Eng et al., 1986; Sessions, Olsen and Garland, 1989; Murphy, 1993b). The issue of how long and short term log production planning can be integrated in a feasible way, which enables the modelling of the various levels in sufficient detail, has also not been demonstrated in the literature.

The research reported here is an attempt at providing a modelling framework which can be used for developing log production plans that are globally optimal at both the short and long term levels, and that enables the features specific to the various planning levels to be modelled at a level of detail that is sufficient for implementation.

Chapter 3

The Integrated Planning System

A detailed description of the integrated planning system which is proposed for modelling the multiple period log merchandising problem is now developed. The proposed structure comprises three planning levels: (i) medium-term tactical harvest scheduling; (ii) short-term tactical harvest planning, and; (iii) operational scheduling. The models at the different planning levels are developed and solved in an integrated manner, based on the hierarchical planning paradigm. An overview of hierarchical planning systems in general, hierarchical planning applications in forestry, and of the proposed hierarchical planning framework are presented in sections 3.1 – 3.3 of this chapter. A detailed description of the major decisions that are addressed at each decision level, and formulations of the models at each of the planning levels are described in section 3.4.

Underlying the log merchandising system is a yield description method which is used to define the production capabilities of a resource by log classes. This yield description system is described in sections 3.4.2, and a bucking model, *XCut*, which was developed for implementing the yield description system is described in section 3.4.1. In the proposed planning system, solutions of log mix production plans are developed within LP harvest scheduling and log allocation models, and the details of this are described within description of the formulations of each separate model in section 3.4. A method was developed in this study for controlling outturn, and which also links production planning at the stand level and bucking implementation at the single stem level, and this is described in section 3.4.7. In section 3.4.8, a discussion of the data requirements for implementing the planning system, and how these relate to the inventory and yield forecasting practices which

prevail in New Zealand, and to forest and stand record systems in general, is presented.

3.1 Hierarchical Planning Systems

Hierarchical planning systems evolved and developed as a reaction to the perception that most organizations are organized in hierarchical levels. Such levels have fundamentally different decision making functions, that differ with respect to the features listed below (Hax and Meal, 1975; Bitran and Hax, 1977; Hax and Golovin, 1978; Bitran, Haas and Hax, 1981; Gunn, 1991):

1. level of management responsibility;
2. scope of decisions;
3. level of information detail;
4. length of planning horizon, and;
5. degree of certainty and risk of data and assumptions.

Hierarchical planning, therefore, developed as a technique for coordinating overall decision making, while enabling features specific to each level to be incorporated in the modelling. Such systems reduce the complexity of the modelling and of the actual decision making by partitioning the overall problem into smaller, easily manageable parts, although this may be at the expense of acceptable weakening of linkages between the sub-models. Another reason for the development of such systems is that data at detailed levels are usually uncertain when aggregate plans are made. Such decisions are therefore best postponed until the instance before a job commences, when the data are more certain. Large scale modelling approaches solve detailed and aggregate plans together, but this leads to decisions at the detailed level being made much too early.

In hierarchical systems, the purposes of the different levels of decision making, and their main features are defined as shown below (Hax and Meal, 1975; Bitran and Hax, 1977; Hax and Golovin, 1978; Bitran et al., 1981; Leong, Ollif and Markland, 1989; Dempster, Fisher, Jansen, Lageweg, Lenstra and Rinnooy-Khan, 1981).

1. Strategic decisions are concerned with policy formulations, capital investment decisions and design of facilities.
2. Tactical decisions are concerned with aggregate production planning, and the medium term implementation of strategic plans, i.e with the efficient use of available capacities and resources.
3. Operational decisions are concerned with detailed production scheduling and implementation that makes a system function.

The following are the basic features of hierarchical planning systems (Hax and Meal, 1975; Bitran and Hax, 1977; Hax and Golovin, 1978; Bitran et al., 1981; Dempster et al., 1981):

1. partitioning of overall problem, and formalizing of linkages between sub problems;
2. separate models are developed for each decision making level;
3. solutions from higher level decisions form part of the constraints for lower level ones;
4. the focus is implicitly on the interactions and linkages between the models, and with designing of the models to fit well together.

Hierarchical systems have found widespread use in planning; for instance in production planning, job shop design and scheduling, distribution system design and control, and vehicle routing and scheduling (Hax and Meal, 1975; Hax and Golovin, 1978; Leong et al., 1989; Dempster et al., 1981), amongst many others. For an extensive discussion of hierarchical planning systems, see Bitran et al. (1981).

3.2 Hierarchical Planning in Forestry

Application of hierarchical planning in forestry have been reported by Gunn (1991), Weintraub and Cholaký (1991), Weintraub et al. (1986), Reinders (1993), Davis and Martell (1993), Laroze and Greber (1991) Hay and Dahl (1984), Morales and Weintraub (1991), Vertinsky et al. (1994), and Lappi et al. (1994). The major hierarchical levels of decision making that are evident in most forestry applications, like other planning environments, are strategic,

tactical, and operational levels. The key features of these decision making levels with respect to forestry applications, are summarised in Table 3.1.

In forestry, the major decisions at the strategic level are related to capacity expansion of both the resource and of processing. This includes such decisions as the amount of land a firm should commit to forestry development and the levels of any further acquisition, and investments in expansion of processing capacity (Gunn, 1991; Hay and Dahl, 1984; Weintraub et al., 1986; Weintraub and Cholak, 1991; Morales and Weintraub, 1991; Vertinsky et al., 1994), and Johnson (1989). Other decisions addressed at this level include investments in road building (Weintraub and Cholak, 1991; Morales and Weintraub, 1991; Weintraub et al., 1986); regulatory concerns, such as environmental issues (Gunn, 1991; Vertinsky et al., 1994; Lappi et al., 1994), and, questions of long term sustainable production of various forest products (Weintraub et al., 1986; Weintraub and Cholak, 1991; Vertinsky et al., 1994; Lappi et al., 1994). Decisions at the strategic level tend to be very broad in scope, are made with highly aggregated data, and which have a high degree of uncertainty, and therefore involve substantial risk. Usually, such decisions involve not only economic objectives, but also other non-quantitative definitions of how the firm or organization perceives itself (Gunn, 1991), and these tend, therefore, to be multi-criteria in nature.

Tactical planning is concerned with timber management and plant production, i.e with resource utilization. In forestry, tactical planning sometimes involve such long horizons that they are often misconstrued as strategic. Tactical planning includes such functions as scheduling harvest and silviculture on existing land bases within specified strategic constraints; guaranteeing long term wood supply; resolving stand level harvesting issues; and planning the logistics of annual aggregate wood supplies (Gunn, 1991; Weintraub and Cholak, 1991; Barros and Weintraub, 1982; Gunn and Rai, 1987). Resource acquisition and investment decisions are not usually modelled at this level, although investments in road building and other issues of access may be considered. In intensively managed plantations, investments in road access are usually pre-determined by any capacity decisions which are made at the strategic level. It can be argued convincingly, however, that such decisions can be considered more appropriately at the tactical planning stage, where they can be addressed with a more realistic level of detail. Decisions at the tactical level have medium-term horizons, are medium scale in scope; involve data that are less aggregated than at the strategic level; have greater certainty than the strategic level; but usually have a moderate degree of risk and uncertainty associated with them.

Table 3.1: Characteristics of Decision Levels in Hierarchy (from Gunn, 1991)

Component of Decisions	Attributes of Decision Component by Planning Level		
	Strategic Planning	Tactical Planning	Operational Control
Objective	Resource Acquisition	Resource Utilization	Execution
Time Horizon	Long	Medium	Short
Level of Management	Top	Middle	Low
Scope	Broad	Medium	Narrow
Source of Information	External & Internal	External & Internal	Internal
Level of Detail	Highly Aggregated	Moderately Aggregated	Very Detailed
Degree of Uncertainty	High	Moderate	Low
Degree of Risk	High	Moderate	Low

Operational level decisions are concerned with execution and control of activities, with the objective of ensuring that the system functions within the constraints of tactical level decisions. Operational decisions, therefore, require a mechanism for ensuring that tactical plans can be implemented as a series of feasible annual plans. The primary goals of planning at this level are feasibility, and minimization of wood supply cost, or maximization of profit opportunities. Operational decisions are the ones that are actually implemented, while some tactical and strategic decisions may not be, due to the dynamic nature of decision making environments. Decisions at this level have short time horizons, have a narrow scope, involve the highest possible detail of data, and have a low degree of uncertainty and risk.

3.2.1 Modelling strategies for the hierarchical levels

Most of the models used for planning at the strategic level are based on either LP or Mixed Integer LP, such as those reported by Weintraub et al. (1986), Weintraub and Cholaký (1991), Morales and Weintraub (1991), Laroze and Greber (1991), Gunn (1991). This is because capacity decisions tend to be discrete in nature. For example, an extension to a processing plant frequently must be done in multiples of a unit capacity or not at all, or a block of available land that often must be acquired in whole or not at all. Many of the harvest scheduling models in the published literature, for example FORPLAN (Johnson et al., 1986), REGRAM (McGuigan, 1992), and FOLPI (Garcia, 1984), are commonly used in strategic planning. When used in this role, such models function as simulators, which are used for exploring the consequences of specified investment decisions.

However, such models are clearly tactical in nature as they deal only with issues of resource utilization, but do not address capacity issues in any direct way. Uses of harvest scheduling models in strategic planning are appropriate when only a single investment alternative is being considered, and the models can therefore be used in analyzing such proposals in what-if scenarios. However, when more than one alternative is being considered, such analyses can lead to significant sub-optimization. In such cases, purposely developed strategic models provide a more substantive basis for evaluation.

Strategic level models which are designed to address capacity issues include those reported by Hay and Dahl (1984), Weintraub et al. (1986), Morales and Weintraub (1991), and Weintraub and Cholaký (1991). Mixed Integer Linear Programming (MILP) is the most commonly used modelling technique for strategic planning in the literature, because of the aforementioned discrete nature of most investments. As only a few aggregated management regimes are usually modelled at the strategic level, Gunn (1991) recommends model I (Johnson and Scheurman, 1977) as likely to be the most appropriate form for modelling forestry production at this level. However, the other model forms, such as model II (Johnson and Scheurman, 1977), and model A (Garcia, 1990) can be just as useful as a basis for strategic planning.

Regulatory constraints, such as sustained yield and ecological concerns, are better addressed at the strategic level as this enables a global evaluation of such issues over a more expansive resource base. When such issues are considered over a small resource base, the

resulting plans can frequently be infeasible. An example of this is the relatively large proportion of area which must be set aside when wildlife habitats are of concern, or the undesirably extreme fluctuations in harvested volumes that can result from imposing age structure regulatory constraints over a small resource base. Because planning at this level commonly involves multiple criteria, goal programming could be a useful basis for developing such plans. But, the focus of this study is on log merchandising in the medium and short-term horizons, and so strategic planning will not be considered in any greater detail in succeeding discussions.

Tactical forest planning models feature most commonly in the published literature. Examples include models such as FORPLAN (Johnson et al., 1986), FOLPI (Garcia, 1984), and those reported by Gunn and Rai (1987), Hay and Dahl (1984), Barros and Weintraub (1982), Johnson and Scheurman (1977), Garcia (1990), Reed and Errico (1986), Allison (1987), McGuigan (1992), Lappi et al. (1994), Vertinsky et al. (1994), and Jamnick (1990). These correspond to planning for forest estates, which are examined in greater detail in the succeeding sections.

Operational planning systems are usually highly specific to the problem being evaluated, and are therefore quite diverse not only in the techniques employed, but also in the structure of the actual models. Operational decisions mainly involve scheduling implementation and log allocation decisions on stands scheduled for harvest at the tactical level. Such models are usually based on LP or MILP, although Gunn (1991) cites the case of use of a simulation model in operational planning. Such models include those reported by van Wyk (1983), McGuigan (1992), Maness and Adams (1991), Reinders (1993), Eng et al. (1986), and Laroze and Greber (1991), amongst others. This type of model is used extensively in the forest industry, although few of these have been reported in the published literature (Gunn, 1991).

3.3 The Proposed hierarchical Planning Structure

The hierarchical structure which is proposed for integrating the multiple period log merchandising problem is related to the system proposed by Gunn (1991), Weintraub and Cholaký (1991), and Weintraub et al. (1986) for modelling long, medium and short-term forest utilization and management planning. However there are major differences with these earlier examples, not only in the decisions addressed at the various levels, but also

in the proposed formulation of the actual models. Nevertheless, it is useful to examine first the structure proposed by Gunn (1991) in detail, and then to compare and contrast it with the structure proposed in this study.

The structure proposed by Gunn (1991) consists of three different levels: long range and medium-term tactical models, and an annual aggregate wood supply model. Table 3.2 shows an outline of the structure, with the decisions addressed and the form of the models at the various levels. In this and the other hierarchical forms discussed by Weintraub and Cholaký (1991), Weintraub et al. (1986), Gunn (1991), the modelling is based on segregating the estate into geographical entities - regions or zones. A long term tactical (Gunn, 1991) or strategic plan (Weintraub et al., 1986; Weintraub and Cholaký, 1991) is next developed, which provides input and output recommendations for each zone. A lower level tactical model is then used to model each zone in greater detail, under the input and output constraints imposed by the higher level plan. The aggregation criteria for these hierarchy of models is based primarily on geographical divisions, although there may be secondary aggregation on the basis of strata uniform in yield capabilities or management prescription within each zone.

In the system described by Gunn (1991), the long range tactical model addresses the problem of ensuring long term wood supply by various log classes by region, while maximizing net revenues from available land holdings. The recommended model type is either model II or model A. The medium-term tactical model disaggregates the long range plan, and provides more detailed input and output prescriptions for each stand within the region. Gunn (1991) recommended a model I as a basis for modelling this level, because of the flexibility it provides for modelling stand level management schedules. However, as discussed by Garcia (1990), both model II and model A can provide just as much flexibility in this regard. The short-term tactical model is then used to disaggregate the medium-term tactical plan down to the level of detailed annual plans. This last model addresses the issues of log production, allocation and mill scheduling, with constraints of harvesting and transport systems and access, and market demands and prices.

The system described in Gunn (1991) was proposed for modelling production from temperate forests, which have much longer rotations than IMPFEH, which contribute the bulk of forest production in both Kenya and New Zealand. Consequently, the time horizons and period widths in the long and medium range levels need to be reduced by a factor of 3 to 5 times, to reflect Kenyan and New Zealand conditions. However, broad conclusions

Table 3.2: The hierarchical structure proposed by Gunn (1991)

Planning Level	Issues Considered
Full Integrated Model	Zone based Industry Sub-model 10 year time periods Planning Horizon: 150 – 200 Years Formulation: Model A Reserve Margins Replanning every 1-5 years Objective: max. net revenues Output: Production targets by zones
Zone Model	Stand Based Separate model for each zone production flows (sawlogs & pulp logs) Period widths: 5 years Horizon: 20 – 50 years Objective: minimize delivery costs Annual replanning Formulation: Model 1 Output: Harvest schedule
Short Term Tactical	Stand Based Model harvest, transport, & mill allocation Standard LP, no growth Planning Horizon: 1 – 5 years Period widths: 3 months - 1 year Objective: maximize revenues Output: annual cutting plans
Operational model	Stand based Objective: crew scheduling, machine scheduling & maintenance, road location & building, mill scheduling & maintenance, road location & building Objective: Minimize costs, ensure feasibility Weekly replanning

Table 3.3: The proposed hierarchical modelling structure

Planning Level	Issues Considered
Medium Term tactical	Crop type based Wood flow by aggregated log sorts 1–5 Year time periods Planning Horizon: 15–30 Years Formulation: Model A
Short Term Tactical	Stand Based Model Road and Landing Locations MILP - facility location model Minimize Wood delivery costs Period widths: 3 months – 1 year Horizon: 1–5 years
Operational Scheduling	Logging Unit Based Model Weekly log allocation & delivery Crew and machinery scheduling constraints Mill scheduling Planning Horizon: 1–3 months Period widths: 1 week – 1 month

regarding the model structures and issues addressed are still relevant, but minor variations are needed to reflect the individual planning contexts.

The modelling structure proposed in this study comprises three hierarchical levels, like that of Gunn (1991). These levels are medium-term tactical and short-term tactical models, and an operational scheduling model. Table 3.3 shows the components of the hierarchical structure and their major features, which are examined in detail below.

3.3.1 The medium-term tactical model

This model level corresponds to components of both the long-range and medium-term tactical models in the structure proposed by Gunn (1991). However, a crucial difference

is the fact that the resource is not aggregated into geographical zones for modelling purposes. Instead, the forest estate is categorized into crop types, which are either strata comprising timber of any age class growing according to a uniform yield table, or are strata subjected to a similar management prescription. A single stand can therefore comprise a crop-type. The modelling is done with crop-types as the basic units of management over the entire estate. Thus the medium-term tactical model develops a plan covering the entire resource, instead of developing separate plans for various zones. In this respect, the approach at this modelling level is similar to that described by Davis and Martell (1993). Unlike the structure proposed by Weintraub et al. (1986), therefore, a column aggregation procedure which ensures consistency between strategic and tactical level plans is not required.

The main objectives of the modelling at this level are:

1. to develop a management plan that maximizes economic returns from the existing land base;
2. to define harvest and silvicultural schedules which guarantee medium-term wood supply by log quality classes from the existing land base, with a profit maximizing objective;
3. to optimize log merchandising options (principally log mix production plans) over the short and medium-term, by integrating the balancing of short and medium-term wood supply for prevailing and projected market demand by log quality classes;
4. to develop a plan that satisfies other regulatory goals, such as environmental concerns, sustained yield, even flow, or non declining yield requirements.

3.3.2 The Short-term Tactical Model

The basic objectives of the modelling at this level are to disaggregate the solution from the higher level into detailed annual harvest plans, and to address issues of access for harvesting purposes. The specific objectives of this level are:

1. to ensure consistency and feasibility between medium and short-term tactical plans;

2. to focus on disaggregation of medium-term plans to annual wood supply plans, and to optimize short-term merchandising strategies when constrained by recommended outputs from the medium-term plan;
3. to disaggregate production plans from the stand level to individual logging setting or group of settings level, which form the basis of operational scheduling and implementation;
4. to prescribe, as a major component of production plans at the setting level, detailed log mix production plans with the goal of meeting log supply commitments, and which are consistent with solutions from the medium-term plan;
5. to optimize the location and construction of landings, while taking into consideration the types of harvesting crews and equipment available, the topographical conditions, the characteristics of the resource, and potential merchandising options for the resource.

Because scheduling of crews and actual harvest implementation are done at the setting or group of settings level, the solutions from the short-term plan are directly implementable at time of harvesting. The purpose of this level is, therefore, to propose the optimal location and construction of roads and landings for stands planned for harvest over the following two to five years. Because construction of landings and roads is done at least two years ahead of harvesting, this provides added flexibility at lower planning levels for allocating crews to a larger choice of harvesting units, as a means of improving value realization. For horizons of 3 years or longer, there may be a need to represent growth in the model.

3.3.3 The Operational Log Allocation Model

This is the lowest level in the proposed structure, the main objectives of planning for which are to:

1. schedule weekly production and wharf inventory by log types for each production unit, i.e logging settings or groups of settings and logging crews;
2. allocate crews to harvesting units while considering crew relocation costs;

3. model in detail log allocation when constrained by harvesting crew availability and costs, and in response to fluctuating weekly demand for various log assortments.

The solutions from this level are implemented directly at time of harvesting, in terms of crew scheduling and log production. Because of the very short time horizon, growth need not be presented here.

3.4 The Planning Models

This section provides a detailed description of the development, formulation, and implementation of the various models used in the integrated planning structure proposed above.

3.4.1 The XCut Stem Bucking Optimizer

The stem bucking problem can be considered as comprising two inter-related but separate problems, the single and multiple stem (stand or forest) problems. At the single stem level, the problem is one of determining how to convert a stem into logs in order to maximize returns. Mendoza and Bare (1986) described the multiple stem problem as one of determining a bucking policy which results in production of the required log types in a desired mix. The multiple stem problem thus comprises not only decisions on how to convert stems into logs, but also involves that of determining the optimal allocation of logs to markets and utilization processes.

The single stem decision is constrained only by the unique form and profile of each stem, and by the specifications (form and profile) and value of desired products (log types). In the multiple stem case, due consideration is also given to aggregate demand and supply, in addition to the stem profile and end product constraints. The multiple stem problem cannot, therefore, be solved efficiently by a single stem model alone. This is because the optimal strategies for each stem within a stand or forest are unlikely to yield properly balanced quantities of the required log types, as decisions for single stems are made without due consideration of market demand. The multiple stem problem is discussed in greater detail in later sections of this thesis.

The single stem bucking problem is analogous to the one-dimensional knapsack class of problems well known in operations research. However, there are two factors specific to stem bucking, which make it unique in this class of problems. The first is that tree stems have variable taper and distinctive distributions of quality features, which have the effect of imposing additional constraints on the decision, because each log type can be cut only from specific sections of a stem due to quality and size requirements. This is despite the fact that the required decision is still along a single dimension, length. This is unlike, for instance, uniform rolls of paper in the paper trim problem where, uniformity of the material mean that a length of paper can be cut at any point along a roll. The second factor which makes it unique is the multiple nature of the units of measure (metres for stem length, centimetres for stem diameter, cubic metres for product size classes and dollars for value), which makes solutions of the problem by methods such as integer programming intractable (Eng, 1982).

XCut is a single stem bucking model (the acronym stands for CROSSCut). It was developed primarily for use in generating detailed pre-harvest information on how a resource can be converted into logs, although it can also be used for determining optimal bucking strategies for single stems. The bucking optimization within the model is driven by the Dynamic Programming (DP) formulation of Pnevmticos and Mann (1972), with some modifications, and was developed and implemented in the Prolog programming language.

The DP formulation of Pnevmticos and Mann (1972) now forms the basis of many stem bucking optimizers, and has been and implemented by Eng et al. (1986), Threadgill (1987), Lembersky and Chi (1986), Deadman and Goulding (1979), and Maness and Adams (1991), amongst many others. The basic scheme in this formulation is to evaluate the bucking at uniform, discrete intervals along the stem called stages. The evaluation starts at one end of the stem, and proceeds recursively in stages to the other. The decision required at each stage is the cutting strategy which would optimize the value of the stem up to that point, if the optimal strategy for the rest of the stem is known.

The stage is the basic unit of the evaluation, and the lengths of all the log types must therefore be multiples of the stage length. The definition of stage length used in this study is similar to that of Eng (1982), Eng et al. (1986), Deadman and Goulding (1979), Faaland and Briggs (1984), Threadgill (1987): it must be a common multiple of all log types that can be cut, and it must also be less than or equal to the minimum difference in length between all the candidate log types. The most commonly used stage lengths in New Zealand are

0.1 m and 0.3 m, which are common multiples for most log types. The latter is the more common. The shorter the stage length, the greater the number of stages along each stem, and the greater the number of log length combinations that can be cut from a stem. This increases the computational effort by orders of magnitude, and it is therefore prudent to use the longest possible stage length to improve solution time.

The evaluation can start from either end of the stem, with identical results. Starting at the base of the stem is the most intuitive strategy, however, and is the approach adopted in the *XCut* model. It has been suggested by Eng (1982) that this is also the more efficient computation strategy, although any such efficiency gains are probably marginal. With each stage is associated a state and a state configuration. With the evaluation started at the base of the stem, the state and stage are then equivalent, and the state is then the distance to that stage from the base of the stem. The state configuration is then the optimal log to cut at the stage, its quality, value, and small end diameter. At each stage, the required decision is the state which optimizes the cumulative value of the stem up to that point, and is called the optimal sub-policy for that stage.

The evaluation proceeds recursively over the merchantable portion of the stem, and produces an optimal sub-policy for each stage. The optimal cutting strategy for the stem is the optimal sub policy at the stage equivalent to the top of the stem. Appendix A contains a more detailed description of the mathematical formulation. Experiences with the environment used for developing and implementing the *XCut* model, Prolog, are also presented in that Appendix, as well as the detailed format of input data, and the structure of the output files.

The *XCut* model takes as inputs two text files comprising a log specification file and a stem data file. The output from the model is a file providing an aggregate summary of the volume, value, average length and average Small End Diameter (SED) of each log type for the stems processed in an evaluation. The model also has an option which provides the optimal bucking strategy for each stem in the data file, if required. Entry of data into the input files can be done with any text editor, but must be in a format suitable for the *XCut* model.

The model was developed principally for use in characterizing stands in terms of their potential yield by log quality classes. This is similar in some ways to the method described by Deadman and Goulding (1979), but with some crucial differences. Like that method, the process is a two stage one. The first stage is a field sampling one, in which plots are

established within stands of interest. The heights and diameters of the trees within the plots are measured, and the major grade determining features along the stems are also noted. The second stage is an analysis phase, in which bucking of the stems within the plots is evaluated with a bucking model. The cumulative results from each evaluation are then projected over the whole stand, by the proportionate area of the stand covered by sample plots in the analysis.

There are two major differences between *XCut* and MARVL (Deadman and Goulding, 1979) field procedure and simulations. The first is in the log types into which the bucking simulator bucks the stems, and the second one is in the way quality features along a stem are recorded. The former is a central feature of the outturn assessment methodology proposed in this study, and is discussed in greater detail in section 3.4.2. In the MARVL system, a dictionary is first compiled that relates primary stem features to how these affect suitability of stem section for cutting into the log types of interest. During the field stage, quality changes along stems are then recorded by noting the primary features, and then recording these as the changes in suitability of stem sections for cutting into the various log types.

In contrast, for the *XCut model*, only the primary features of the stem are recorded. This means that there can be more than one feature along a stem section: for instance a swept stem section can also have a large branch occurring within it. This differs from the MARVL technique, where the quality changes cannot overlap, but stem suitability classes are, instead, progressive along a stem. In *XCut*, the input of primary features is encouraged by requiring that both a starting and an ending point for all features should be entered.

The potential advantage that this provides with the *XCut* system is that the data can be re-used, even if there are drastic changes in the log mixes in a bucking evaluation. The MARVL system does not provide this flexibility, because the recording of stem quality in terms of suitability codes masks the primary data. As a result, if there are major changes in market demand from the log mixes that prevailed at the field inventory stage, then a new field inventory may very well be needed. The major uses of the *XCut* model are examined further in section 3.4.2.

3.4.2 The Outturn Assessment Methodology

Outturn from a stand or forest is the yield realized at time of harvesting, and is usually described by volumes in the various log assortments. Outturn can be potential, or actual, depending on whether it is merely predicted, or actually realized. Actual outturn is the realization after harvesting, and is a function of characteristics of stems within the resource, and the decisions made during stem conversion. The two are related, however, because the function of outturn prediction is to provide a both a forecast and plan of the log mixes which can be produced or realized at time of harvesting. Rationalization of differences between the two outturn components is what comprises yield reconciliation. Actual outturn and yield reconciliation are, however, not within the scope of this study and are not considered any further.

Predicted outturn, on the other hand, is the projected realization from a stand when constrained by stem characteristics and potential stem conversion strategies. At the planning stage, it is a function of characteristics of stems within the resource, market demand by log sort, and the list and value of the candidate log types used in a bucking evaluation. Forest managers are interested in planning outturn from a resource because it forms the basis of cash flow projections, and also because it enables value maximization goals to be evaluated. Planning of outturn also enables a manager to develop more effective harvesting and marketing strategies for the resource.

The multiple stem bucking problem is essentially one of outturn prediction, when constrained by characteristics of stems within the resource on the one hand, and of market demand and values of various log assortments on the other. Planning of outturn can therefore be considered as comprising three components: characterization of the resource in terms of its potential to produce logs of given quality classes; optimization of potential outturn; and, control of outturn. This last component forms the link between production plans at the stand level, and conversion at the single stem level.

In New Zealand, the first two components of outturn planning have traditionally been solved with the MARVL system by performing bucking evaluations following the method described in section 3.4.1 (Deadman and Goulding, 1979; Goulding, 1993; Threadgill, 1987)). This approach frequently leads to a lack of balance between supply and demand, the causes of which have already been discussed. In this study, the three components are considered separately in an attempt to address the limitations in existing methodologies. The method

proposed here involves developing a system for characterizing the resource by its capability to produce a given set of log quality classes. These provide the upper bounds on production of log types for a log allocation model, which generates an optimal log mix for each stand (outturn) for the periods of interest. The system for optimizing outturn is built into the formulations described in section 3.4.5 and 3.4.3. A third routine is used to generate new log specifications for controlling outturn at the implementation stage, which system is described in section 3.4.7.

3.4.2.1 Characterization of the resource by quality classes

Characterization of stands in terms of their potential to produce various log quality classes in New Zealand, is frequently done by market log types, for instance as described by Deadman and Goulding (1979). A consequence of this, however, is that whenever there is a change in the planned log mix (for instance, in response to fluctuations in market demand) a new analysis maybe necessitated. The other problem with such an approach is that there are frequently a large number of market grades which can be cut from a resource. However, characterization of a stand's yield potential by such a large number of grades is meaningless for planning and implementation purposes. A third problem results from the unsystematic effects of using market log prices for controlling the bucking evaluation, which is examined in greater detail below.

The approach proposed in this study involves describing the yield potential of stands by a few stem quality classes. Such classes can represent either aggregations of market log grades, or can be on some other basis of classification suitable for an organization's planning purposes. An example of such stem quality classes can be, for instance, the log grade aggregations proposed by the New Zealand Conversion Planning Conference (Whiteside and Manley, 1986), which may be a system used throughout that organization.

In this study, the quality classes used for this purpose are determined by aggregating all the log types to be modelled into a few, mutually exclusive groups. Each of the log types within a class need to be broadly uniform in quality requirements of both stem features and end diameter tolerances. For every specification variable, each class acquires the most extreme specifications of log types within the class. For instance, the minimum length is defined as that of the shortest log type in the class, similarly for the minimum small and large end diameters of the log. The same holds for maximum specifications, where a class

acquires the largest specification variable for a log type within it. Log types with similar quality requirements, but which have very different size requirements, may be separated into different classes to avoid potentially infeasible yield descriptions. The stands are then characterized by their potential to produce these quality classes, by evaluating how stems in the resource can be bucked into the quality classes with the *XCut* bucking model.

Another variation of the method proposed here from the MARVL one, is in the prices of the log classes used for controlling the bucking evaluation. Relative or market log values are commonly used as a means of controlling stem conversion in a bucking evaluation, by using these to indicate to the model product a managers product preferences. Changes in such values are also frequently used to effect adjustments in log mixes from a bucking evaluation. The direction (increase or decrease) in the volume of a log type, the value of which is changed in an evaluation, can be predicted to some extent. However, what is frequently not realized, is the unsystematic effects that changes in one log type's relative value can have on the magnitude and direction of changes in the volumes of all other log types. This factor has recently been demonstrated to some extent by Goulding (1993).

An illustrative example of the unpredictable effects of log values on the volumes of the various log assortments cut in a bucking evaluation is given in Figure 3.1. The example comprises ten log types, both pruned and unpruned. In the example, all the log types have been given fixed length requirements for the purpose of demonstration, and these lengths and other minimum specifications are shown in Table 3.4.2.1. The specifications shown in the table are minimum, and a log can, of course, be cut from stem sections with higher quality features. Stem quality class A refers to straight pruned logs, B to straight unpruned logs with small branches, C to unpruned logs with large branches and limited sweep, and D to residual pulpwood.

In this example, the value of log type 4 is progressively increased from \$ 75.00 up to \$ 255.00 in increments of \$ 20.00. \$ 175.00 is the value of other log types with similar quality requirements. The top value of \$ 255.00 is higher than the value of the next higher quality log type, which has the most stringent quality requirements of all the log types. The results of the changes in value of this log type on the volume of all the other ones from bucking evaluations are shown in Figure 3.1. From the figure, it can be seen that the volume of the log type of interest is cut in minimal quantities up to a threshold value of \$155.00, beyond which the volume rapidly increases at the expense of log types with similar or higher quality requirements. This also affects the volumes of both shorter and

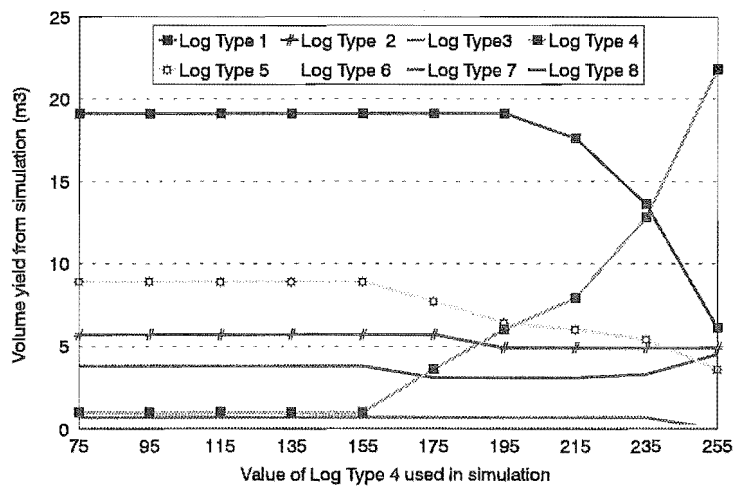


Figure 3.1: Effects of variations in value of one log type on volumes of all log types in a bucking evaluation

Log Type	Length (m)	Quality	min. SED (cm)	Value (\$/m ³)
1	6.1	A	30	250
2	4.1	A	30	250
3	12.1	B	30	175
4	8.1	B	30	175
5	5.5	B	30	175
6	4.1	B	30	175
7	11.1	C	26	130
8	7.4	C	26	130
9	3.7	C	26	130
10	3.0–6.0	D	10	50

Table 3.4: Log Type specifications used to illustrate effects of log values on volume yield

lower quality grades, which results from some sections of stems being upgraded to the now more valuable grade.

It can also be seen in the figure, that it is not possible to predict the magnitude of a change in the volume of a log type resulting from any change in its value. It is even more difficult to predict the volume changes in other log types resulting from a change in value of one log type, and the situation would be considerably more complex if the values of more than one of the log types were modified. Note that all but one of the log types used in this example have fixed length requirements. If more of the log types had random length requirements, the fluctuations in volumes of the log types can be expected to be much greater, due to the considerably larger number of log quality and length combinations that would be feasible in any evaluation.

Clearly, therefore, use of log values as a means of controlling outturn results in unsystematic fluctuations in yield that do not facilitate planning. Use of log values as a means of controlling outturn for planning purposes could be justified if the volumes of the log types resulting from changes in log values can be determined in a systematic manner, but this is not the case. As it is also not possible to predict if a market price for one of the log types yields the maximum recoverable volume for that log type, use of these in bucking evaluations yields results that represent only a snapshot of the possible yield scenarios.

The approach adopted in this study is to eliminate the uncertain effects inherent in using

log values for controlling outturn when characterizing stands in terms of their yield potential. This is achieved by a heuristic determination of the values used in the bucking evaluation. If the purpose of characterizing a stand's yield capability by quality classes is to express a stand's maximum capability to supply each of the quality classes that maximizes stand value, then the process follows directly from this, as explained below.

1. The first step is to determine the quality classes which are to be used for characterizing the stands. In this case, these are determined by aggregating all the log types into a few categories, with logs within each class requiring uniform stem qualities.
2. The classes are then ranked into a hierarchical order of decreasing stringency in quality requirements.
3. The price of the highest quality log is then determined iteratively, by increasing the value of the class and then evaluating bucking possibilities at each iteration until there is no increase in the volume of the log class that is cut.
4. The values of the other classes in the hierarchical order are then determined sequentially in the same manner. However, an additional condition is that the value of the class chosen should lead to the highest possible volume of the log type cut, without this leading to a reduction in the volumes of classes that are higher in the hierarchical order. The list of log types used in the bucking analysis must therefore include the quality class being considered, and all the other classes higher than that class in the hierarchy.

The quality classes, and their values arrived at in this way, are then used in a bucking evaluation to characterize stands by their maximum yield capability. Outturn from the stands is then optimized with a log allocation model, which recommends the optimal mix of logs to produce from each stand and period. The yields determined by the bucking evaluation form upper bounds on the production of the various log types during log allocation. Because a log type can be supplied from quality classes with similar or higher quality requirements, downgrading may be necessary as a marketing strategy, which capability must be built into such models. The stand characterization system described here forms the basis for the multiple period merchandising system proposed in this study. The manner in which outturn optimization is accomplished within the system is discussed in detail in succeeding sections.

3.4.3 The Tactical Harvest Scheduling Model

The model form here corresponds to the numerous harvest scheduling models in the published literature (Barros and Weintraub (1982), Johnson and Scheurman (1977), Garcia (1984), Gunn and Rai (1987), Davis and Martell (1993), for example). The model type proposed for modelling this level is the model A formulation of Garcia (1990). This model form was selected because of the flexibility it allows for modelling silvicultural and harvest prescriptions at the crop-type level. The method also has the attraction of the availability of a problem formulator, FOLPI (Garcia, 1984), which allows the type of problem studied here to be described with great flexibility. The FOLPI systems allows transfers between crop types in any specified period ranges in an horizon, which is an important requirement in intensively managed short rotation plantations. The main features of the modelling at this level are listed below.

1. NPV maximization as the primary objective.
2. Resource descriptions or yield tables are done by aggregated log quality classes.
3. Model form is model A (Garcia, 1990), although models I and II (Johnson and Scheurman, 1977) could also be used.
4. Log quality class volumes are allocated to marketable log grades by exploiting the joint nature of log production, with downgrading used as a strategy for matching demand and supply by log types.
5. Planning units are stands and log types in early periods of the horizon, but these can be aggregated into crop types and log quality classes for later periods, in order to reduce model size.
6. Regeneration is allowed only into selected generic crop types.
7. Market demand is aggregated into volumes of the various log grades.
8. Types of flow constraints are capacity based, with the levels reflecting market demand forecasts
9. Model is run on a rolling horizon basis, with replanning done every 1–3 years, or sooner if required.

10. Uncertainty is catered for through:

- reserve margins on production by quality class;
- high discount rates, and;
- rolling horizon implementation.

11. Time periods are single years over the horizon. The time periods can however be aggregated for later periods, to yield a varying period width model such as that of Barros and Weintraub (1982), and Papps and Manley (1992).

Figure 3.2 is a network representation of the flow of areas between periods, crop types and age classes in this formulation, which is adapted from Garcia (1984) and Davis and Martell (1993). The example illustrated in the figure shows the flow of areas into and out of one crop type over n age classes and a planning horizon of t periods. A crop type can comprise a single stand if desired. The minimum age of harvesting (thinning or clearfelling) in the example is m years, and all stands are clearfelled after age n .

Each rectangular node in the figure represent the area of a crop type in an age class in each period, and the round nodes represent areas available for replanting into the same or other crop types in the period. The triangular node represents an ending state for the resource, that is determined either by constraints imposed by the resource manager, or by the optimization process in the absence of any such constraints. The arcs are of two types, growth arcs are directed towards the top right end of the figure, while harvest arcs are directed downwards towards the bottom right corner. Because m is the minimum age of harvesting, there are no harvest arcs leading out of age classes below this.

At the beginning of each period, the forest is described in terms of the area in each crop type and age class. Some of this area is cut in the period, and the residual area advances into the next age class at the beginning of the next period. The harvested area is replanted either into the same or a different crop type. The volume harvested in a period is a product of the area of the crop type that is cut, and a yield table for the crop type and age class. The harvest may either be final (clearfell), or intermediate, such as thinning. The difference between these is that there is residual yield after an intermediate harvest, while the area becomes available for regeneration after a final harvest. Costs and revenues are treated as products and are modelled either as intermediate (for example, costs of silviculture, tending, and revenues from thinnings) or final, for example, clearfell revenues and final harvesting costs.

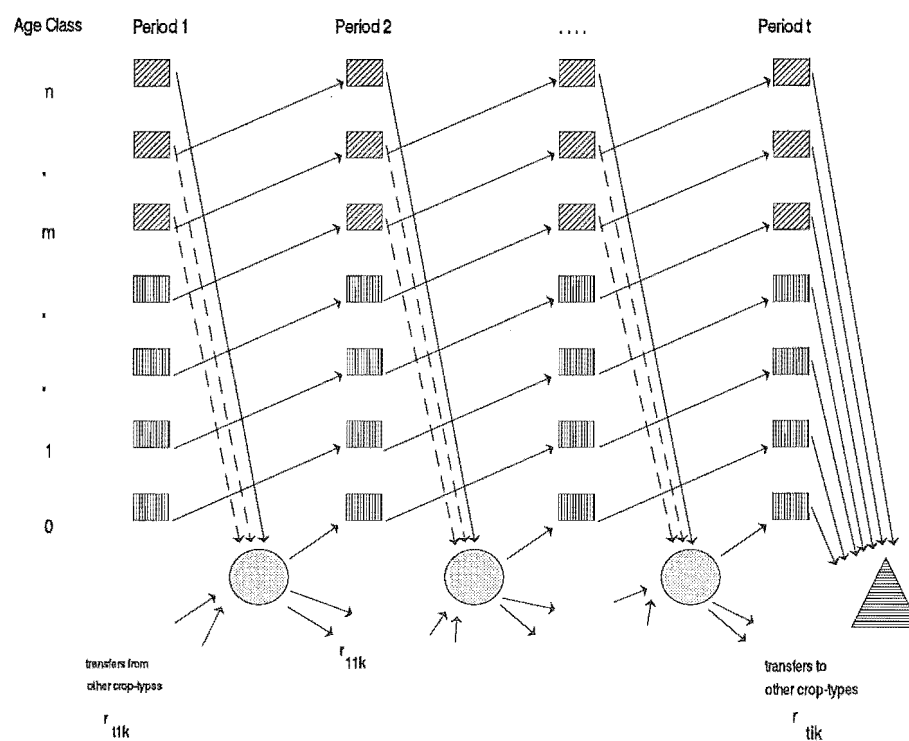


Figure 3.2: Flow of areas in a model A formulation

Area can be transferred between crop types in any period and age class, although this is not shown in the diagram. The manner in which this is permissible is determined by constraints imposed by a manager. For instance, this can be done by limiting the transfers from a crop type only into a limited set of other crop types, or by restricting the age ranges at which such transfers can take place. The ending state of the estate after period t is determined by specified constraints; for instance, that there must be a minimum area in certain age classes at the end of the horizon, or by a minimum ending inventory. In the absence of any such constraint, the ending structure of the estate is determined by the optimization process, which, under a revenue maximizing objective, may recommend cutting all material which has attained the minimum age of harvest. The treatment of end of horizon effects, which are propagated through the terminal periods of a plan, must then be given careful consideration.

Garcia (1990) discusses how this formulation can be extended, by having, for instance, one or more bareland crop types to account for unplanted land or new land available for planting, or the representation of unavoidable delays in regeneration through use of dummy age classes. Other management concerns, such as with the utilization sub-sector, can be incorporated into the model, possible methodologies of which are also presented in that reference. Manley and Threadgill (1986b) demonstrate extension of the formulation to modelling of log allocation and transportation.

The LP formulation directly follows from the flow of areas shown in the diagram. There are four groups of decision variables in the formulation. The first represents the area cut from a crop type and age class in a period. The second represents the residual area in a crop type, age class and period, which moves into the next age class in the next period. The third one represents the area of a crop type harvested in a period and available for replanting into any of the crop types. The last represents the area of a crop type in an age class that is transferred into other crop types in a period. There are two types of constraints in this formulation: those supplied by the user, such as a minimum age of clearfelling for a crop type, and the other are structural constraints, which enforce area conservation at the nodes. The major components of the formulation are shown in the equations below (Garcia, 1984).

3.4.3.1 Decision variables

- x_{ijt} = residual area in crop type i , age class j after cutting in period t which moves into the next age class in the next period
 y_{ijt} = area of crop type i age class j cut in period t
 r_{itk} = area of crop type i cut in period t and replanted into crop type k
 z_{ijkt} = area of crop type i age class j transferred to crop type k in period t
 a_{ij} = initial area in crop type i cut in period t and replanted into crop type k

3.4.3.2 Indices

- i = $1 \dots I$: crop type index
 j = $1 \dots J$: age class index
 t = $1 \dots T$: time period index
 k = $1 \dots I$: crop type index
 s = $1 \dots T$: time period index

3.4.3.3 Forms of structural constraints

$$\sum_j y_{ijt} = \sum_k r_{ikt} \quad \forall i, t \quad (3.1)$$

$$\sum_k r_{tki} = \sum_{s=t+1}^{T+1} y_{s,i,(s-t)} \quad \forall i, t \quad (3.2)$$

$$a_{ij} + \sum_k z_{kji} - \sum_k z_{ijk} = \sum_{s=1}^{T+1} y_{s,i,(j+s-1)} \quad \forall i, j \quad (3.3)$$

$$y_{tij}, r_{tik}, z_{ijk} \geq 0 \quad (3.4)$$

The constraint in equation 3.1 relates the area of a crop type in all age classes that is cut and replanted into all croptypes in a period. The constraint in equation 3.2 relates the area

replanted into a crop type in a period, to the area of that age class that is cut in all future periods. The last constraint (equation 3.3) relates the initial area in a crop type and age class, to the area of that age class transferred into and out of the crop type in a period, and to future harvests of that age class from that crop type in all future periods.

In this study, the tactical harvest scheduling model was formulated and solved with FOLPI (the acronym stands for Forest Oriented Linear Programming Interpreter) forest estate planning package (Garcia, 1984). The system takes as input a description of the problem in forest management terms. This is done in the form of yield tables and user defined constraints. The yield tables provide a detailed description of the crop types, the area in each age class by crop type, and the yields (both final and intermediate) by age class for each crop type. The user constraints give permissible flow of areas through the network in 3.2. Such constraints include allowable replantings; allowable inter-crop type transfers for the various age classes; minimum and maximum ages of clearfelling; area of bareland available for replanting and the crop types these can be planted into; and regulatory constraints such as non declining yield, even flow, or capacity constraints.

FOLPI converts the problem description into an LP formulation of appropriate file format, submits this file to an LP solver, and, once an optimal solution has been found, translates a summary of the results back into tabular form. Solutions provided by the system include the area harvested by crop type in each period, the area replanted into each crop type in every period, and inter crop-type transfers in every period. A separate reporting function describes the status of the resource in each period, in terms of the area under each age class by crop type.

The FOLPI package has an extension, which can be used to model the allocation of various log assortments to disparate markets or mills. The solution provided by the log allocation report comprises volumes by log assortments cut from each crop type in every period, and the volumes of the various log assortments that is allocated to each mill or market.

3.4.4 Modelling Short-term Harvest Planning

The model at this level is intended to disaggregate the medium-term tactical model into detailed, annual plans. The other objectives at this level of modelling are to integrate and optimize the selection of harvesting systems (a function of topographical conditions, resource characteristics and production capacity), location and construction of landings, and

the planning of log mix production. Road construction is not considered at this level as, in fast growing tropical and sub tropical plantation forestry, road construction at harvesting is not considered an important issue. This is because a decision to enter into forest production requires that roads be built to facilitate regeneration and tending, so that at time of harvesting, such roads would normally already be in existence.

Models that integrate all the required decisions at this level are not evident in the literature. Weintraub and Cholaký (1991) discuss a model that facilitates design of a road system within a strategic harvest planning model. However, because the problem is modelled at the strategic level, it does not consider design of a system of landings and settings, which is what is required for the lower level operational scheduling.

A study which looked at this issue at the level required within the hierarchical framework in this study, is reported by Dykstra and Riggs (1976). The paper describes a model for designing a system of settings, and for selecting and allocating harvesting systems to the logging settings. The model formulation is based on facility location theory, and the landings are considered as facility locations to which logging systems and production capabilities can be allocated. In their method, feasible landing locations are developed from topographical and other technical data, and a system of landings is then optimally selected from these with a mixed integer LP. The solution from the model also provides an allocation of areas of stands or forests to the various settings. In this model, however, management prescriptions are considered as exogenous, and so there is no consideration of log production plans, nor of the trade-offs between setting locations and log production plans, which is the focal point of this study.

This level of model was not developed in this study due to limitations of time, but instead, possible approaches that can provide a basis for modelling the issues at this level will be discussed. A modelling system which can provide the required decisions at this level would integrate the facility location aspects of the model reported by Dykstra and Riggs (1976), and an extension of these to consider optimization of log merchandising. The model would therefore provide not only solutions of optimal landing locations and a selection of harvesting system to be used within these, but also a tentative log production plan for each setting. A mixed integer programming model based on facility location theory, such as that of Dykstra and Riggs (1976), interfaced to an information system with components for storing and accessing data; for developing feasible facility locations; for

formulating and solving the model; and for interpreting and reporting the resulting solution. The details of the likely components for the system are discussed individually below.

1. Part of the dataset needed for generating feasible landing locations relates to topography. These form the basis for generating a feasible set of locations, which can be done either manually or with specialist programs. A digital terrain model, particularly Geographical Information Systems (GIS), would be suitable for this purpose. The landing locations can be generated by application programs written within or outside the GIS, or manually with the aid of the GIS and other geographical data. Davis and Martell (1993) provide an example of how this can be done in silvicultural planning, and (Vertinsky et al., 1994) provide an example of such integration in regional planning. Due to the complexity of setting layout, audio-visual data describing the state of the forest could greatly facilitate the generation of such layouts. Use of such data has been demonstrated by the pioneering work of Brann, Corcoran and Li (1992) with the use of multimedia technology. These approaches could form a useful starting bases for the development of suitable systems.
2. Also required are data on yields by stands, or at the more detailed setting level, if available. This calls for a stand record system, which can be integrated within the GIS or it can be a stand alone system external to it. Davis and Martell (1993), Lappi et al. (1994), and Vertinsky et al. (1994) provide examples of forest planning applications that integrate GIS, database management system (DBMS) and LP, which is a good indication of the potential in this regard. Whittaker and Brown (1991) provide another potentially useful example of how modelling with LP can be interfaced to a DBMS from which technical coefficients for the LP are generated.
3. A problem formulator for accessing the data from the GIS, a DBMS and other sources, and which uses the data to generate a formulation of the problem in a format suitable for a solver, would be required. The formulator can be a part of the DBMS or GIS, for example as in Davis and Martell (1993), Lappi et al. (1994) or external to it as in the application described by Whittaker and Brown (1991).
4. A mixed integer LP package, or specialised algorithms that exploit problem-dependent structures, for solving the formulation.
5. A report generator which translates the solution from the solver back into a form suitable for interpretation by managers. This can be integrated within the GIS or

DBMS, or can be an external program. However, to increase the utility of such plans, there is a need to translate the solutions into a form suitable for graphical display and analysis with the GIS. Such reports could be even more useful to managers if presented in conjunction with visual imagery using multimedia technology, such as has been demonstrated by Brann et al. (1992).

The mixed integer LP (MILP) formulation of the problem is likely to lead to a large-scale program, due the fact that 0–1 variables are required for every feasible landing location, logging system, and period. Such large-scale MILP problems can now be solved with general purpose solvers, as is evident from the fact that models with more than 1 000 integer variables, and even much larger ones have been successfully solved with general purpose solvers (Nemhauser, 1994; Johnson and Nemhauser, 1992; Barnhart, Johnson, Nemhauser, Sigismondi and Vance, 1993). However, the model is likely to have considerable special structure, for instance the “cascading fixed charge” structure of the model described by Dykstra and Riggs (1976). Such special, problem-dependent structures can be exploited in the development of special purpose solution heuristics which yield better solution times. Nemhauser (1994) discusses various heuristics that can be used for solving (0–1) models, and others which can be used to aggregate (0–1) variables and for formulating such models as a means of improving the ability to solve them. Such heuristics could prove useful in the development of model formulations and solving strategies that yield reduced solution times.

3.4.5 The Operational Log Allocation Model

The model at this level disaggregates the short term log production plans to detailed weekly harvest crew schedules and log production plans at the setting or group of setting level. A mathematical formulation was developed which can be used for modelling these issues, and this formulation and the essential features of the model is described in this section. A model generator written in the Prolog programming language, which was developed for generating formulations of problems in a format suitable for solving with appropriate solvers, is also described.

3.4.6 The Mathematical Formulation

The following notation is used in the description of the formulation below. Small letters are reserved for decision variables and time indices, upper case letters denote data (coefficients), and Greek letters are used to denote integer (0–1) variables.

3.4.6.1 Decision Variables

y_{jkt}	=	volume (m^3) of log type j produced in period k and supplied to markets in period t
a_{it}	=	area of stand i harvested in period t
θ_{it}	=	1 if crew h is allocated to stand i in period t if the crew was not already in the stand in period $(t - 1)$
δ_{hit}	=	1 if crew h is allocated to stand i in period t and 0 otherwise
δ_{0it}	=	Extra harvesting crew capacity (m^3) required in stand i in period t
q_{nit}	=	yield (m^3/ha) of quality class n from stand i in period t
l_{nit}	=	volume of quality class n material from stand i downgraded to quality class $(n + 1)$ in period t
g_{nit}	=	volume of quality class $(n - 1)$ material from stand i downgraded to quality class n in period t
u_{jt}	=	slack in production of log type j in period t
x_{ijt}	=	volume of log type j produced from stand i in period t
x_{jt}	=	total volume of log type j produced in period t

3.4.6.2 Data

P_{jt}	=	market price of log type j in period t
C_{it}	=	unit cost ($\$/\text{ha}$) of harvesting stand i in period t
R_{hit}	=	cost of relocating crew h from any other stand to stand i in period t
R_{0it}	=	penalty cost for allocating slack crew δ_{0it} to stand i in period t
F_{hit}	=	operating costs for crew h in stand i in period t
V_{nit}	=	yield (m^3/ha) of quality class n material from stand i in period t
M_{ht}	=	production capacity (m^3) of crew h in period t

B_{jt}	=	penalty cost on slack in production of log type j in period t
E_{ijtk}	=	cost of wharf storage (\$/m ³) for log type j produced in period t for sale in period k
D_{jt}	=	market demand for log type j in period t
A_i	=	total area of stand i available
τ_j	=	maximum permitted storage time for log type j

3.4.6.3 Indices

i	=	$1 \dots I$: stand Index
j	=	$1 \dots J$: log type Index
j_n	=	$1 \dots J$: log type Index
n	=	$1 \dots N$: quality class Index
t	=	$1 \dots T$: period/time index
h	=	$0 \dots H$: crew index
k	=	$t \dots (t + \tau_j)$: storage time index

3.4.6.4 Constraints

$$\delta_{hi0} = 0 \quad \forall h, i \quad (3.5)$$

$$\delta_{hit} - \delta_{hi(t-1)} - \theta_{hit} \leq 0 \quad \forall i, t, (h \neq 0) \quad (3.6)$$

$$\sum_i \delta_{hit} \leq 1 \quad \forall (h \neq 0), t \quad (3.7)$$

$$\sum_n q_{nit} - \sum_h M_h \delta_{hit} \leq 0 \quad \forall i, t \quad (3.8)$$

$$\sum_t a_{it} \leq A_i \quad \forall i \quad (3.9)$$

$$a_{it}V_{int} - q_{int} = 0 \quad \forall i, n, t \quad (3.10)$$

$$q_{nit} + g_{nit} - l_{nit} - \sum_{j \in J_n} x_{ijt} = 0 \quad \forall i, n, t \quad (3.11)$$

$$x_{jt} - \sum_i x_{ijt} = 0 \quad \forall j, t \quad (3.12)$$

$$x_{jt} - \sum_{k=t}^{t+\tau} y_{jkt} = 0 \quad \forall j, t \quad (3.13)$$

$$\sum_{t=k-\tau}^k y_{jkt} + u_{jt} - D_{jt} = 0 \quad \forall j, t \quad (3.14)$$

3.4.6.5 Objective Function

Maximize $Z =$

$$\sum_{j,t} P_{jt}x_{jt} - \sum_{i,t} C_{it}a_{it} - \sum_{h,i,t} R_{hit}\theta_{hit} - \sum_{h,i,t} F_{hit}\delta_{hit} - \sum_{i,j,t,kneq t} E_{ijtk}y_{jkt} - \sum_{j,t} B_{jt}u_{jt} \quad (3.15)$$

3.4.6.6 Description of the formulation

Figures 3.3, 3.4, and 3.5 are network representations for an example problem of crew allocation over stands and periods, material flows, and allocation of products to inventory and demand respectively. The problem depicted in the figures comprises two stands, a single crew, and three time periods. Stand yield is described in three quality classes from which 4 log grades can be produced, two from the second quality class, and one each from the other classes. All log products can be stored for a maximum of one period.

In Figure 3.3, the columns represent possible crew allocations in each period. The first row is a dummy stand, which represents an idle status for the crews. Crew allocation over time

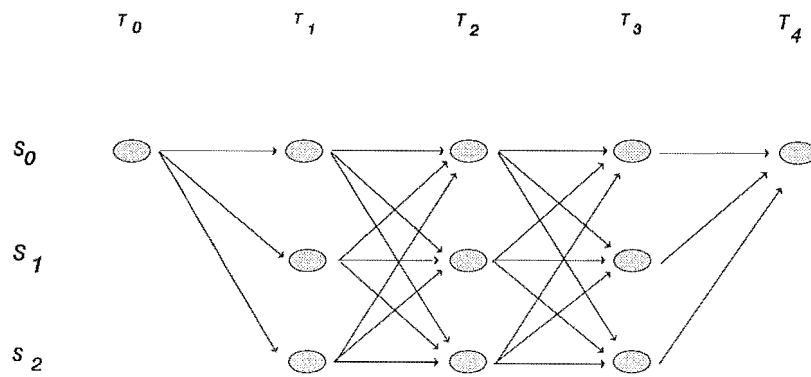


Figure 3.3: Network representation of possible crew allocation between two stands over three time periods

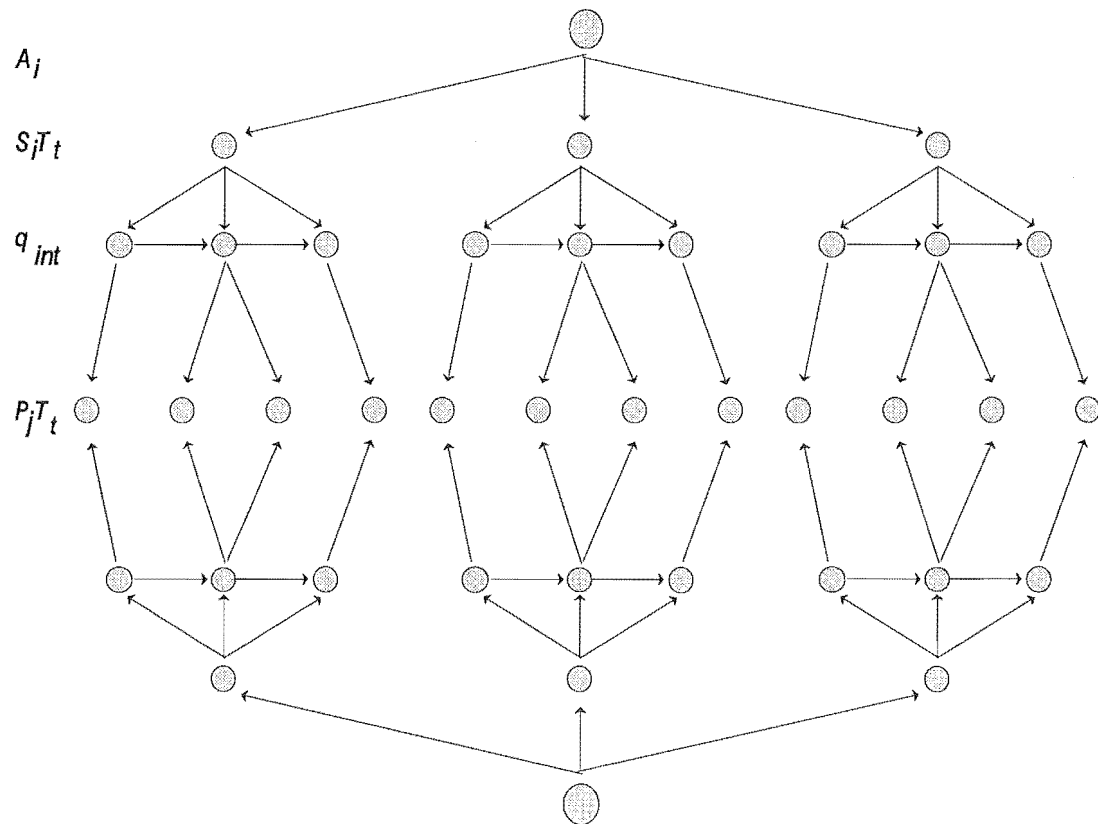


Figure 3.4: Network representation of material flows within two stands over three time periods

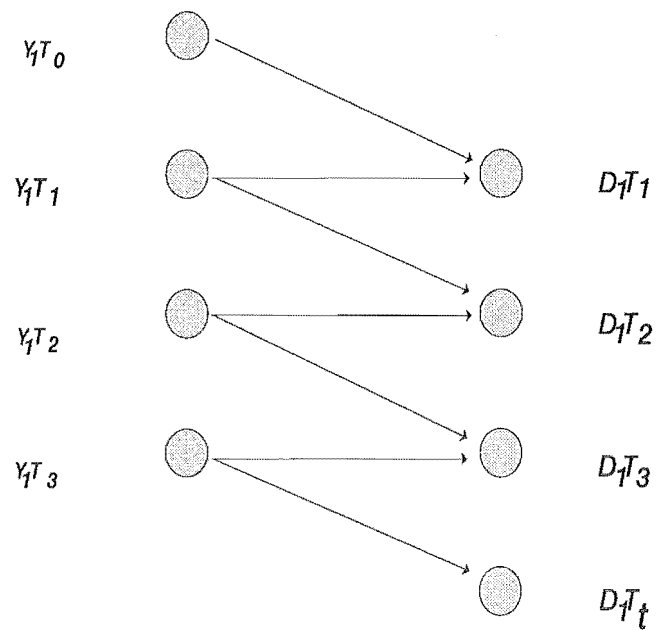


Figure 3.5: Flow of produced logs to and from inventory, and to meeting market demand

periods is from left to right. A crew can be allocated either to any one of the two stands in a period, or to an idle status. At the beginning and end of the horizon, the crew is allocated to an idle status. Any crew can be allocated to only one of the rows in a period.

In the material flows shown in Figure 3.4, part of a stand is harvested in each period of the planning horizon. This yields a fixed proportion of the various log quality classes. Material of a quality class produced from a stand in a period can be used either to produce log types which have similar quality requirements, or some of it can be downgraded to the next quality class. For all quality classes, except the highest, the total volume available in a period is the sum of the volume of that quality class harvested, and contribution to this from material downgraded from the a higher quality class. Some of this volume is then allocated to production of the various feasible log products, while the rest is downgraded to the next lower quality class. The total volume of a log type produced in a period is then the sum of contributions from all stands in that period. As shown in Figure 3.5, some of this volume is then allocated to meeting demand in the present period. The rest of the material is allocated to inventory, for use in meeting part of demand in subsequent periods.

The mathematical formulation of the log allocation model follows closely from the figures, with additional constraints that conserve flow at the various nodes. The constraints in the formulation are discussed in three parts; those relating to crew allocation in Figure 3.3, and those relating to resource flows in both Figures 3.4 and 3.5 respectively. Constraints 1 to 3 below relate to Figure 3.3, and determines crew allocation to the stands. Constraint 4 links crew allocations in Figure 3.3, to the area of any stand harvested in Figure 3.4. Constraints 5 to 8 apply to Figure 3.4, and relate the area of each stand harvested in a period, to the volume of every quality class and the log types produced all stands in the period. Constraints 9 and 10 relate to Figure 3.5, and are concerned with allocation of material to and from inventory, and to meeting market demand.

1. Constraint 3.5 ensures that all crews are allocated to an idle status in period 0.
2. Constraint 3.6 determines relocation costs for each crew in a periods. This is assessed as the positive integral difference between the allocation of crew h to stand i in period t and the allocation of crew h to stand i in period $(t - 1)$ for all crews, stands and periods.
3. Constraint 3.7 ensures that any crew, h , is allocated to only one stand in any period t .

4. Constraint 3.8 is the crew allocation constraint, which links Figures 3.3 and 3.4. The total production capacity of all crews allocated to a stand in period t should be greater than the total volume of all logs produced from the stand in period t . To ensure feasibility, the variable θ_{hit} is used to pick up any slack.
5. Constraint 3.9 defines stand area upper bounds: The sum of the area of each stand cut in all periods should be less than or equal to the total area of the stand available, for all stands.
6. Constraint 3.10 collects the total volume by quality classes harvested from a stand: total volume of a quality class produced from a stand in a period is equal to the product of the area of the stand harvested in the period and the yield of the quality class from the stand, for all stands and periods.
7. Constraint 3.11 determines log production and downgrading for all log types for a quality class. The total volume of a quality class produced from a stand in a period, plus material downgraded from the higher quality class, less material downgraded to the lower quality class, should equal the total volume of logs of all grades produced from the quality class and stand in the period.
8. Constraint 3.12 sums up the total volume of a log grade produced from all stands in each period, and links Figures 3.4 and 3.5.
9. Constraint 3.13 allocates the total volume of a log grade produced from a stand in a period to meeting market demand for all feasible periods. Material not used for meeting market demand in the period is allocated to inventory and used to meet market demand in the next period.
10. The market demand constraints, 3.14, ensures that the supply of a log grade from production, inventory and slack in a period should equal market demand. The variable u_{jt} is used to pick up any slack in supply of log type j in period t .
11. The Objective function (equation 3.15) has six terms: the first term is the revenue accruing from the sale of log products. The second term is the cost of harvesting each stand in each of the periods, which is a function of the area of each stand harvested. The fourth term represents crew operating costs, incurred by all non idle crews in all periods. Penalties for slack in productivity of crews allocated to a stand in a period are included within this term. The third term is the relocation costs for all crews in all periods. The fifth term is the cost of wharf storage for all products produced in

a period, and supplied to markets in subsequent periods. The last term represents the penalties for slack in production of all products in all periods.

This formulation can be extended to include consideration of transportation costs and equipment constraints, with little conceptual difficulty. However, the data requirements for such an extension are likely to be quite extensive, involving development of transportation cost variables for each transport method, and for every log sort from each setting or group of settings to every destination, and would be likely to increase the size of such models substantially. It is debatable whether a finer resolution in the modelling of log transportation can impart significant benefits to the allocation plans.

3.4.6.7 A Goal Programming extension of the formulation

The formulation of the quarterly log allocation model is elastic in the sense that the major constraints can be violated, but at a penalty. The model can therefore not be infeasible, but users are required to check the level of slack variables, to determine if any infeasibilities exist before using the solution. Such model elasticity mimics the real world, in the sense that most decisions in the real world can be violated, but at a price. The major disadvantage with such a formulation is the problem of setting penalty weights for slack variables in the formulation. If the penalty weights for slack production are too low, then the model uses the cheap resources to satisfy the constraints, even if these could be met from available resources.

Another problem with cheap slack resources is that these can make the problem unbounded as the objective function can be improved infinitely, if there are no demand constraints. The better approach is therefore to set the penalties at a very high level, so that, if the problem is infeasible, then such costs dominate the solution. The model then attempts to minimize these costs, at the expense of the other elements of the objective function. But this approach also has the problem that such costs can mask the contributions of other elements to the objective value, which may potentially offer better insight into the problem.

There are two possible approaches to overcoming this problem. The first one is to run the model in a two step fashion, with the first run having as its sole objective to minimize the use of external resources, i.e., slack in crew allocations and the production of log types.

The full model is then solved as a second step after information on the minimum quantities of extra resources, if any, required to make the problem feasible, have been obtained from the first stage solution. If the objective value for this solution is greater than zero, then the activities of the slack variables indicate the minimum amount of resources (slack in log production and crews) required to make the problem feasible. The problem can then be solved after specifying appropriate penalties for violation of the constraints, by reducing the lower bounds on the necessary variables, or by making available extra resources as required. On the other hand, if the objective function value is less than or equal to zero, then the model is feasible, and can be run without the penalties and slack variables.

In the method, the first objective function is formulated to minimize slack production, by minimizing the penalties for using additional log and crew resources. Costs of the supplementary resources are used instead of the actual resources, in order to make the units of the objective function elements uniform. The objective function then becomes:

$$\text{Minimize } Z = \sum_{j,t} b_{jt} U_{jt} + \sum_{h,i,t} f_{oit} W_{oit} \quad (3.16)$$

with all the other constraint forms unchanged. The cost of the additional resources, b_{jt} for the log products, and f_{oit} for the crews, must be high enough as to make use of available resources more attractive. The model, in a revenue maximizing form, can then be solved once the issues of feasibility have been evaluated and resolved, from the activities of the slack variables in this model.

The other alternative is to reformulate the model into a Goal Programming (GP) form, with minimization of the usage of surplus resources as one of the goals in a multiple objective set. The level of achievement of this goal would give an indication of the additional resources required to make the problem feasible. The GP can be either a sequential elimination one, such as pre-emptive GP, or a weighted sum GP. However, a problem with the pre-emptive form of the GP formulation would be closely related to that of the elastic LP one; that is, the difficulty with setting priority levels of the different goals. Weighted sum GP, either in MINSUM or MINMAX form, would therefore appear to be the more attractive approach to solving this problem.

The multiple objective approach demonstrated here is a weighted sum GP in MINMAX form. In this form, a set of objective functions is formulated, which corresponds to each

of the goals of interest. Initially, these are solved as separate problems, with the constraint space unchanged. The objective values of these models are then treated as targets, and the GP problem is formulated with the objective of minimizing the largest underachievement among all the goals. For purposes of illustration, a GP formulation is demonstrated here with the objectives listed below. Other objectives, such as maximization of value recovery, and minimization (or maximization) of the supply of specific log sorts in some time periods, amongst many others, can be evaluated just as easily.

1. maximize net revenues;
2. minimize the cost of using external resources, and;
3. minimize total costs.

The first goal has the same objective function as the deterministic formulation, and includes the costs of using extra resources. The objective function for the second goal is similar to the first objective function in the two stage approach, which is given in equation 3.16. The third objective comprises a subset of the elements of the deterministic formulation objective, and includes all the objective function elements in the goal, except the revenue contributions from log sales, as shown in equation 3.17.

$$Max Z = - \sum_{i,t} c_{it}a_{it} - \sum_{h,i,t} r_{hit}\theta_{hit} - \sum_{h,i,t} f_{hit}\delta_{hit} - \sum_{i,j,t,k} e_{ijtk}X_{ijtk} - \sum_{j,t} b_{jt}U_{jt} \quad (3.17)$$

Once the individual LPs has been solved, each goal becomes a constraint in the GP, with the respective objective values as a target on the Right Hand Side (RHS). The GP objective function is then formulated to minimize the single largest weighted deviation of a goal from its respective target, amongst all the goals. However, as the goals may have different units for the objective values, the deviations can be expressed in relative terms as percentage or fractional achievements. For this illustration, the objective function elements of the goals are expressed in the same units, currency. It is frequently easier for managers to specify acceptable deviations from targets on percentage basis, rather than in absolute units. In this problem, the deviations are expressed fractionally, but this causes no losses in generality. In the above problem, the GP objective function is:

$$\text{Minimize } Z = v \quad (3.18)$$

Subject to the goal constraints in equations 3.19 to 3.21, in addition to the other MILP constraints in equations 3.5 to 3.14.

$$\begin{aligned} \sum_{j,t} p_{jt} X_{jt} - \sum_{i,t} c_{it} a_{it} - \sum_{h,i,t} r_{hit} \theta_{hit} - \sum_{h,i,t} f_{hit} \delta_{hit} - \sum_{i,j,t,k} e_{ijtk} X_{ijtk} - \\ \sum_{j,t} b_{jt} U_{jt} + G_1(v/w_1) \geq G_1 \end{aligned} \quad (3.19)$$

$$- \sum_{j,t} b_{jt} U_{jt} - \sum_{h,i,t} f_{oit} W_{oit} + G_2(v/w_2) \geq G_2 \quad (3.20)$$

$$\begin{aligned} - \sum_{i,t} c_{it} a_{it} - \sum_{h,i,t} r_{hit} \theta_{hit} - \sum_{h,i,t} f_{hit} \delta_{hit} - \sum_{i,j,t,k} e_{ijtk} X_{ijtk} - \\ \sum_{j,t} b_{jt} U_{jt} + G_3(v/w_3) \geq G_3 \end{aligned} \quad (3.21)$$

In this formulation, G_m are the separate targets for each goal m , w_m are the weights placed on each goal m , and v is the largest underachievement (deviation) amongst all the goals.

3.4.6.8 Potential Computational Problems with the formulation

There are potential problems, apparently with symmetrical solutions or cycling, as a result of the crew relocation constraints in both the GP and deterministic MILP. This can occur if two or more crews have the same productivity and costs (both of relocation and operating). The effect of these would be to increase the solution time substantially because of the symmetry. This results from the branch and bound phase of the MILP solution procedure searching through nodes with alternative optima. In a previous problem not reported here, with four crews, all having similar productivity and costs, the optimizer was allowed to run for 96 hours without proving optimality. No improvement in the objective value was realized over the best solution obtained after fifteen seconds, even after

the model had run for this long. This indicates the important effects that symmetry can have on the solution time of problems with integer variables.

In this application, the possibility of such problems was reduced by adding small random deviates to the productivity and cost coefficients of each crew. Another approach was adopted as a means of improving solution time, but which also has the side effect of reducing potential problems with symmetrical solutions. This is the imposition of an integer optimality tolerance on the objective value during the branch and bound phase of the solution. The tolerance which was selected for use here is that any node which is unlikely to yield an integer objective value that is better than the incumbent best integer value by at least 10 % is not explored. As symmetrical solutions do not improve the objective value, such nodes are therefore more efficiently pruned during the branch and bound process.

3.4.6.9 Computer model Implementation

The quarterly log allocation model was developed in the LINDO¹ mathematical programming package (Schrage, 1991). A program was developed in the Prolog programming language, for use in generating algebraic formulations of the problem in a file format suitable for solving with LINDO. The problem files can also be solved by other mathematical programming packages which require relatively similar formats, such as XA² and CPLEX³, with minor modifications.

The program takes as input three files: a case file, a crews file, and a market file. These files provide a description of the problem in a simple and intuitive format, that allows flexibility in modelling different problems. The case file describes the name of the problem, the length of the planning horizon, the number of stands and their identities, the number of stem quality classes, and the yield of the stands by quality classes. The crews file describes the identity of the crews available, their productivity, operating costs, and relocation costs. The market file describes the log types to be modelled, the quality classes from which they are obtained, market demand and prices by log type in each period, and whether storage is permitted and the maximum period for which it is permitted, and the cost of wharf storage per cubic metre for each log type.

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The program generates a formulation of the problem and writes this in a text file, which can then be solved with LINDO or other mathematical programming packages which take similar input file formats. A detailed description of the input file formats and sample data for the program is provided in Appendix B.

3.4.7 Controlling log Outturn

A component of log merchandising that has received relatively little attention in the published literature, is the interface between production planning and field implementation. This should be an essential feature in log merchandising plans because production planning is performed at the stand level, but field bucking is a stem by stem process. Each tree has its own unique attributes of size (form) and quality features (profile), and therefore requires to be treated differently during conversion. It is, therefore, often impossible to realize the targets of a production plan as a sum of implementation decisions on conversion made at the single stem level. Specific guidelines for each log production plan for a stand should be provided to field buckers, therefore, to ensure that conversion decisions made for each stem are driven towards target log assortment volumes in the production plan.

This problem is more significant if the yield description system described in section 3.4.2, and the outturn optimization method described in section 3.4.5 is used. This is because downgrading is employed as a market driven production strategy with the method. Downgrading presupposes a change in grading rules, in the form of making more restrictive the quality requirements for the log assortments from which material is downgraded. There may be less need for this in systems where the yield description is performed with a bucking model to market log types and specifications, and which are then used in field implementation. Even then, log values play a very important role in the log mix determined by bucking models at the planning stage, as discussed in section 3.4.2. As it is extremely unlikely that field buckers can make an evaluation of trade-offs in log values with the efficiency of a bucking model in field situations, provision of precise physical guidelines as a means of controlling outturn has much to recommend it.

A method was developed in this study which can be used to link production planning and field implementation, and which can also be used to test the feasibility of a log production plan. The system was developed primarily as a method for controlling outturn,

with the objective of ensuring that volume targets in a production plan can be realized as a sum of single stem conversion decisions made in the stump area or at skids. The basis of the method is a heuristic procedure, which generates new specifications for selected log grading variables. The principal variables for this purpose are length, small and large end diameters, and acceptable quality features. The new specifications, when used in field bucking, are intended to drive the realization from field bucking towards the targets in the production plans.

The heuristic method is based on the yield description system presented in section 3.4.2. The method involves iteratively generating new specifications that yield volumes that are progressively nearer to targets in the production plans, and then performing bucking evaluations with the new specifications. The process stops when the volume yields by log assortments is within acceptable tolerances of the targets. In this way, new specifications are generated which yield volumes of the log types in the required levels. New specifications are developed for a setting or stand for every period in which there is a change in either the mix of log types, or of proportions of the log types planned. Details of the process is described below.

1. Firstly, the results of the yield description system developed as outlined in section 3.4.2 are collected.
2. A log production and allocation plan is then developed and solved, such as with the system described in section 3.4.5.
3. Log types in the production plan are listed and then ranked in order of decreasing stringency in quality requirements, and by log values in the case of equal stringency. The values used for determining yield description for the class into which each log type belongs in section 3.4.2, is then noted against the log type.
4. Using the specifications for the log type and the value for the quality class, the following procedure is carried out:
 - (a) Evaluate bucking of the log type using the same inventory data used for developing the yield description in section 3.4.2;
 - (b) Note the volume of the log type obtained. As can be seen from the rationale for the yield description system in section 3.4.2, this can only be equal to or greater than the volume recommended by the production plan;

- (c) If the volume obtained is that recommended by the production plan, then there is no need to modify the specifications for the log type. If this is not the case, then the specifications are modified by the process below.
- The quality requirements for the log type are made more restrictive, and then the bucking evaluation is repeated. For instance, some of the less preferred lengths, or some of the more undesirable quality features for the log type can be deleted. It is important to do this progressively, and iteratively, as such tightening of specifications for the log type can reduce volume yields by a larger margin than required. If these changes are too restrictive, i.e. too little volume is realized, then there is need to relax the restrictions up to a point at which the volume realized is either greater than or equal to that required.
 - If the volume realized is still greater than that required, then the minimum SED specification is used next as a controlling variable. The minimum SED is tightened iteratively as follows.
 - Arbitrarily select an SED that is much higher than the specification for the log type, and perform another bucking evaluation. If this still yields a higher volume than required, then select an even higher SED, and perform another simulation. This process is performed repeatedly until an SED is found that is too restrictive, i.e. leads to a lower volume realization than is required for the log type.
 - New SED specifications are then generated by the method of bisection, which method is described in many numerical analysis texts (e.g. Schwarz (1989)). The bisection method is used to determine the SED between the minimum specification, and the overly restrictive one determined above, within a sequence of intervals of increasingly smaller lengths, as below.
 - From the two SEDs, one too high and the other too low, the new estimated SED is determined as the halfway interval between the two.
 - An evaluation is performed, and the half within which the required SED falls is selected. This is determined as follows: if the volume yield at this new SED is too low, then the required SED is in the lower half, otherwise it is in the upper half.
 - If the required SED is in the lower half, then this SED becomes the new higher SED and the process is repeated between the incumbent lower

SED and the new higher one. If it falls in the upper half, then this becomes the new lower SED, and the process is repeated between the new lower SED and the incumbent upper SED.

- New SEDs, which are progressively closer to the required one, are generated iteratively with this method until, an SED is found that yields the required volume for the log type within an acceptable tolerance.
- (d) The new length, stem quality and minimum SED specifications determined for the log type are then the final ones to be used for field implementation of the log type.
5. New specifications for the next log type in the ranked list is then developed. This is done in the same manner as described above. The important difference is that the list of log types used in the bucking evaluations must include both the log type under consideration, and the log types ranked higher in the list and for which new specifications would already have been developed, and using the new specifications for the log types.
6. The process is repeated for all the log types in the list, except the last one, the specifications for which do not need to be modified as it contains all residual material of merchantable size.

Thus, new specifications are generated for every stand and period in which there is a change in production plans. However, because of the joint nature of log production, it is only when the volume proportions of the various log types change, and not just actual volumes in a production plan, that new specifications require to be developed. An illustration of the changes in log SED and volume yields that result from these with a case study is presented in the next chapter.

3.4.8 Data Requirements for the Planning System

The data required for modelling with the hierarchical structure proposed in this study is wide ranging, and includes the elements below.

- Stand data, including location within the estate, area, crop history, latest available inventory and yield data.

- Yield projection systems: for forecasting future yields at both the tree and stand levels, and appropriate tree taper, volume and height models. A necessary component of this would be a diameter distribution model for projecting growth in tree diameters, which is required for outturn assessment with systems based on bucking model evaluations.
- Topographical data, overlaying the stands, and which can be used for determining the suitability of stands for various harvesting systems, and for planning road and landing layouts.
- Market data, including log types, their specifications, prices, market demand for current and future periods, which can be actual or forecasted; binding supply commitments, if any, by log types.
- Data on harvesting and transport equipment; their technical limitations by terrain, piece sizes, costs and other constraints and their numerical availability.
- Regulatory concerns such as environmental considerations with respect to harvesting systems, policy on fluctuations in log supply, required structure of the forest.

The data requirements, with a few exceptions can be met from existing management information systems, the major difference is in the way in which the data are used. The main exceptions are the data for the yield description system in section 3.4.2. However, data from existing inventories can be used with the yield description system, although at the cost of a loss in the advantages of the *Xcut* system discussed in section 3.4.1. Such data can, however, be easily collected under prevailing pre-harvest inventory practices, the only difference being in the method used for describing tree profiles at the field inventory stage.

At the operational level, refined yield estimates at the level of setting and group of settings maybe required. These can be met by establishing a few plots within the settings for localizing stand level yield estimates, or from a new inventory depending on the type of pre-harvest inventory that had been conducted at the stand level. These offer no conceptual difficulty, as they follow standard practices, although at a finer geographical resolution.

The aggregation of stands into crop types at the medium-term tactical planning stage follows from current inventory practices. The disaggregation from crop types to stands is recommended for stands in which a mid rotation inventory has been done. In such cases,

the stands then have unique yield estimates depending on the management history of the stand, but use of standard yield tables for a crop type may mask the effects of the unique history of the stands. Stands below mid rotation inventory age are modelled as belonging to a crop type. A further discussion of the data requirement and the implications of these for the integrated planning system developed in this study is discussed in Chapter 4, within the context of a log merchandising planning case study.

Chapter 4

Using the Planning System: A Case Study

4.1 Background

The planning system developed in this study was applied to a multiple period log merchandising case study problem, as a means of demonstrating and testing its potential uses. Data for the case study were collected from disparate sources and used to formulate a typical planning problem in the plantation forest industry. While the problem is not of a realistic size with respect to the resource base, the log production aspects are defined from detailed market information which prevails in the industry. The problem, therefore, reflects the issues of major concern at a level of detail sufficient to provide some insight into how the system can be used to evaluate major log merchandising decisions. The main difference between the case study and realistic problems is, therefore, only one of magnitude, but not of detail or complexity.

In this chapter, a description of the case study problem and the results of applying the proposed planning approach to the problem are presented. Section 4.2 provides an overview of the planning problem, which comprises a hypothetical forest estate for which a long and short term merchandising plan is required. The next section provides a detailed description of the major components of the log merchandising planning problem, and details of how the problems were formulated and solved in hierarchical order. Because the results from higher level models form the basis for lower level planning, the major results

from higher levels are described before the formulation of lower level problems are presented.

4.2 The Planning Problem

The hypothetical firm is likely to be an integrated forest management and processing firm, in which the processing and forestry sectors are organized as independent profit or business centres. The forestry business is concerned primarily with managing the resource, with logs as the end product. Possible concerns with maximization of downstream processing are therefore considered as being external to the firm, and are not included in the evaluation, unlike in the studies reported by Barros and Weintraub (1982), Gunn and Rai (1987), Maness and Adams (1991), and Hay and Dahl (1984). The resource comprises a total area of 3 682 ha in nine stands of various age classes above minimum age of harvesting (intermediate or final). In addition to these, there are various other stands with varying age classes all below mid rotation, and which have therefore not had a mid rotation inventory. These stands are grouped into one crop-type for modelling convenience, into which all harvested areas from all the other stands are also regenerated.

Logs from the resource are supplied to domestic and export markets. Domestic customers, which may include the firm's processing businesses, negotiate and contract for their wood supply on an annual basis, but there are some fluctuation in short term demand. Some material is also supplied to the spot market as a means of balancing short term log surpluses, and whenever it is economically advantageous to do so. Demand from export markets are driven by shipping schedules provided by the marketing department of the firm for each up-coming planning quarter on a rolling basis. The aim of the forestry business management, is to maximize returns from the resource, while meeting contracted supply and other demand to the maximum extent possible. This is with the aim of maintaining and even to increase the firm's market share.

Demand is specified by volumes of the various log types. Each log type is specified by name, a list of acceptable quality features (such as pruning, branch sizes, and sweep) for the grade, a minimum and maximum length, small and large end diameters, and a market value or price, which may fluctuate from one period to the next. The log length specifications are of two types. Fixed length grades have only a limited number of specified feasible lengths. Random length grades, on the other hand, have a minimum and maximum

specification, and logs can be of any length within this range in specified unit increments, usually 0.1 or 0.3 m. In addition to these, it is also common to specify an average small end diameter for each shipment, and a distribution of lengths as a proportion of the total volume of a shipment. These last specification are important for logs destined for the Japanese and Korean markets, and may vary from one shipment to another, depending on negotiations. The log products for the export market can be stored at the wharf, but only for limited periods due to sapstain and other wood deteriorating agents. Donnelly and Whyte (1994) provide a comprehensive insight into issues of log specifications for both New Zealand domestic and export markets.

The required management decisions can be considered in terms of the medium and short term horizons. At the medium term level, the objective is to develop management strategies and harvest schedules which maximize returns from the existing land base. This involves developing management prescriptions for stands within the estate, that balances both short and forecasted medium term demand to the maximum extent possible. Another decision included within this level is the optimization of trade-offs between short-term log merchandising options, and medium-term timing of harvest for the stands, as a possible revenue maximizing marketing strategy.

At the short-term level, the focus is on scheduling harvest of the stands nominated in the long term plan: to optimize the location and construction of roads and landings required for harvesting; to identify harvesting equipment needs; to develop schedules for harvesting systems and equipment, and; to generate detailed log production plans and decide on allocation of logs to the spot market and to meeting short term demand and other wood supply commitments. The major challenge both here and at the medium term planning level, is to develop production strategies that match characteristics of the resource to markets in an optimal and feasible manner.

The stands and crop types and the distributions of area by age class for each are shown in Table 4.1. The log types to be supplied from the resource and the specifications for these are shown in Table 4.2. In the quality specifications, A refers to pruned, round, peeler quality material; B refers to unpruned round logs with small branches and minimal sweep; C to unpruned logs with moderate sized branches, which can be out of round and can have a limited amount of sweep, and; D refers to residual pulp quality material. The lengths shown in the table exclude a trim allowance of 0.1 m. The log type data, i.e specifications and log values, were obtained from Anonymous (1993).

Table 4.1: Area under each crop-type by age class for the case study

Age Class	Area by crop type or stand (ha)										TOTAL
	GCT	A	B	C	D	E	F	G	H	I	
1-3	415										415.0
4-6	312										312.0
7-9	338										338.0
10-12	346										346.0
13-15	237										237.0
16-18	239										239.0
19											
20	229										229.0
21		263									263.0
22			170								170.0
23											
24				216							216.0
25											
26					40					192	232.0
27											
28						212					212.0
29											
30							22				221.0
31								147			147.0
32									105		105.0
TOTAL	201	263	170	216	40	192	212	221	147	105	3 682.0

Table 4.2: The log types, their prices, lengths and stem quality requirements (from Anonymous (1993))

Log Grade	Quality Spec.	Lengths	Price (\$)
Pruned Sawlogs (PSL)	A	4.0,6.0	280.0
Japanese A (JpJ)	B	12,8,4	165.0
Domestic Sawlog 1 (SL1)	B	3-6	140.0
Japanese J (JpJ)	C	12,8,4	135.0
Domestic Sawlog 2 (SL2)	C	3-6	90.0
Korean (Kor)	C	11,7.3,5.4,3.6	130.0
China (Chn)	C	10,6-8,4	90.0
Domestic pulp (Plp)	D	3.0-12.0	52.0

The inventory data for the various stands which comprise the case study, and which were used for formulating the yield tables for the generic crop type, were obtained from disparate sources. The data for stands above 25 years of age were obtained from pre-harvest inventory for a resource in the Central North Island of New Zealand, but identity of which cannot be divulged for reasons of commercial sensitivity. The data comprised sample plot data, in which the height and diameter at breast height (DBH) of all the trees within each plot were measured, and the changes in quality features up a stem were described and noted. The sample plots comprised strips (transects), each 2 m wide and 100 m long, of which there were at least ten representing each stand.

Data for stands below 25 years of age were collected from the Moi University teaching forest at Cengalo Forest station, near Eldoret in Western Kenya. The data were collected in November 1992 from *Pinus patula* stands, in a manner similar to that already described for the New Zealand data. Details of this sampling strategy for pre-harvest inventory assessment are discussed in Goulding and Lawrence (1992). The differences in the species and condition of the tree crops between the two data sets do not cause any complications in this case study, because the focus is on the planning process, and not on the actual detailed results of the plans *per se*.

4.3 Outturn Assessment for the Case study

The outturn assessment for this problem was done according to the procedure described in section 3.4.2. The process is done in three stages. The first stage involves determining the aggregated log quality classes to be used for characterizing the stand's production capabilities. The second step is to determine the values for each of the quality classes to be used in the bucking evaluation. The last step involves performing bucking evaluation on the inventory data for the stand. The manner in which these elements were performed for the case study problem and the results of these are described in the following sections.

4.3.1 Stem quality classes and Values for Outturn Assessment

The quality classes used for describing outturn from the stands were arrived at by aggregating the market log types into a few, mutually exclusive classes, with the log types within each class having broadly uniform stem quality requirements. The classes formed

Table 4.3: Stem quality class aggregations used for outturn assessment in the case study and the log grade specifications which fall within each class

Quality Class	Quality features	Length (m)		SED (cm)		Value (\$)	Log Types in class
		min.	max.	min.	max.		
Pruned	pruned no sweep	3.0	8.0	30	99	280.00	PSL
Sawlog 1	unpruned small branches no sweep	3.0	12.0	23	99	165.00	SL1,JpA
Sawlog 2	unpruned large branches some sweep	3.0	12.0	18	99	135.00	SL2,JpJ Kor,Chn
Pulp	residual	3.0	12.0	10.0		52.00	Plp

for the problem, and the log types within each are shown in Table 4.3. The last column in the table shows the log types which fall within each of the quality classes, the abbreviated names of which are given in Table 4.2. These quality classes and values were then used as a basis for determining the maximum potential yield from each stand with the *XCut* bucking optimizer. In this process, the quality classes are used as the log types into which the stems from the sample plots can be bucked.

The log values for the quality classes were determined by the process described in section 3.4.2. In this case, the values of the quality classes which meet the criteria presented in that section, were equivalent to those of the highest priced log type in each of the classes. No further evaluation of values to use in the bucking evaluation was, therefore, necessary.

An essential component of bucking evaluations are functions for estimating the volumes of stem sections, and for predicting changes in diameter (taper) along a stem. This is because only diameter at breast height over bark (dbhob) is measured at the inventory stage. A bucking evaluation starts at the base of a stem, which is equivalent to stump height, and then proceeds along the stem to the merchantable height. The diameter over bark (dob), therefore, has to be projected back to stump height, and also to other points along the stem where the cutting of any log is considered. Separate volume and taper functions can be used in this regard, the only requirement being that they provide an accurate prediction

of the required variables.

In this study, one equation was used to estimate both sectional volume and taper. The equation used is a compatible, full polynomial taper function, developed for young crop radiata pine in Kaingaroa forest in the Central North Island. The function, which is referred to as F115 in NZ FRI & MoF (1992), is of the form shown in equation 4.1. Because the equation is compatible, the integral of the taper function between any two points along the stem provides an estimate of the volume of that section, and a separate function for this purpose is therefore not required.

$$\frac{d'^2 K h}{v} = \beta_1 z + \beta_2 z^2 + \dots + \beta_n z^n \quad (4.1)$$

In the equation, z is the relative distance of the sectional height from the top of the tree, which is determined as $z = (h - h')/h$, d is the diameter of the stem at sectional height h' , v is the merchantable tree volume, h is the height of the tree, and K is a constant to convert diameters from cm^2 to m^2 . The coefficients, $\beta_1 \dots \beta_5$ are, respectively, 1.1714, -3.5452, 26.708, -44.31, and 22.686. The volume between two heights along the stem is determined by integrating the taper function over the two limits. An estimate of total tree volume (v), however, is required before equation 4.1 can be used. For the case study, this was provided by a two dimensional volume equation, referred to as T237 in NZ FRI & MoF (1992), which has the form shown in equation 4.2. The notation in that equation is similar to that in equation 4.1, in addition to which d refers to the diameter at breast height (overbark), h is total or merchantable stem height. The coefficients, $\beta_1 \dots \beta_4$ are, respectively, 1.760385, 1.048023, -9.805884, and zero. Temu (1992) gives a detailed description of the use of and development of taper functions, which reference also discusses the potentials and drawbacks of using these and other forms of taper and volume functions.

$$V = d^{\beta_1} \left[\frac{h^2}{h - 1.4} \right]^{\beta_2} e^{\beta_3} + \beta_4 \quad (4.2)$$

The output from the XCut model is the volumes by log types cut from the stems in the sample plots. These volumes must then be expressed on a unit area basis (m^3/ha), which is done according to the relationship in equation 4.3. In the equation, n is the sample plot index; j is log type index; and i the stand index. Vol_{ij} is the unit volume (m^3/ha) of log

type j from stand i ; V_{ijn} is the volume of log type j from sample plot n in stand i ; a_n is the area of plot n ; and N is the total number of plots in the stand.

$$Vol_{ij} = \frac{\sum_{n=1}^N V_{ijn}}{\sum_{n=1}^N a_n} \quad (4.3)$$

The yields obtained in this way provide only a snapshot of the potential of a stand if it were harvested at the point in time when the inventory was taken. Because of accretion, there is need to predict future yield, if the stands are scheduled for harvest in any period, other than the one in which the inventory was conducted. The method of projecting the data that was used in this study is based on the diameter distribution model of Woollons and Hayward (1985). The method is designed for projecting the increment in diameter of stem dbhob classes as a proportion of the total increment in the basal area of a stand between two time periods. Using that approach, growth in dbhob of trees in the sample plots are projected forward to the period of interest, and evaluation of bucking of stems in the plots is then repeated with the new diameters to determine yield for the future period.

There is one drawback that was experienced with this approach as a method for projecting stem diameters for future yield estimation. The problem was encountered with projection of data for stands that had not undergone a final thinning, if such projection was to be done beyond the scheduled thinning age. That simulation model has the capability to project stand tables taking into account any prior thinnings. However, the problem with projecting the data past a scheduled thinning is then how to decide on the stems to remove from each inventory sample plot data, in order for such data to reflect the anticipated state of the stand after thinning. The choice of stems removed from each sample plot can have great effect on the yields by log assortments from the bucking evaluation, and this, therefore, requires further objective consideration. This is the one major issue that limited the application of this approach in the case study.

Another potential problem, although a minor one, is that there are currently no available means for predicting potential changes in the distribution of quality features along each stem as a result of growth. However, such changes are likely to be in the upper sections of the stem, which have both lower value and volume. In fast growing, intensively managed tropical and sub tropical plantations, if the inventory is done at or after mid rotation when most silvicultural operations that affect stem quality would have been completed, then such changes are unlikely to have any significant impacts on the value and volumes of

the log assortments.

In this case study, the projection of yields by log types was done with Woollons and Hayward's (1985) system, but in an indirect and heuristic way. Sample inventory data for a 20 year old crop were compiled for use as an indicative example. The stems in this sample were projected forwards up to age 40 with a spreadsheet implementation of the model. The age of 20 years was selected as a starting point for the projection because it occurs after all thinning operations would normally have been completed, and therefore avoids the above mentioned difficulty with the system. The changes below age 20 for the example were then determined heuristically, by drawing a stylized curve over this period range, including an estimation of volumes removed in thinnings. A bucking evaluation was then performed on the data at five year intervals, and the percentage change in total merchantable volume by age was noted at each age. These percentage changes in total merchantable volume were then applied to the log assortments from the bucking evaluation for the stands of interest, over the period from the age at inventory, to 40 years, starting from the same age on the indicative data. In this way, the data for each stand and crop type were projected forwards to 40 years. The yield tables for each stand and crop type generated in this way are in Appendix B.

4.4 The medium Term Tactical Plan

The major objectives of the medium term tactical planning are to schedule harvesting and silviculture on the existing land base; to guarantee the supply of logs by quality classes to meet demand to the maximum extent possible in the short and medium-term, while maximizing revenues; and to determine the optimal trade-offs between stem conversion options and harvest schedules for the stands. The medium term tactical model was developed with the FOLPI software package (Garcia, 1984), which allows the planning problem to be described in terms familiar to managers. The software package then converts the problem into an LP formulation, and solves it with suitable mathematical programming software. The solution is then translated back into tabular form for analysis and implementation.

The problem description is made through two main mechanisms: yield tables and user defined constraints (NZFRI Ltd, 1992). In addition, other components that control the modelling, such as the length of the planning horizon and the division of this into periods, are

entered in a separate part of the package. The yield tables provide the names of the crop types in the problem; the area in each age class for all the crop types; the volumes by log assortments obtainable from harvesting each crop type; the costs and revenues obtainable from harvesting a unit area of the crop type at any age (either final or intermediate); and the revenues and costs from each age class per unit area of the crop types. The costs can be for such interventions as tending and silvicultural operations, or of harvesting. The full yield tables prepared for modelling this level are provided in Appendix B. The user constraints and other features of the model at this level are listed below.

1. The planning horizon is 60 periods, each of one year. Such a long horizon was selected to eliminate end effects of the modelling, but principal interest is on the first rotation results only.
2. Discount rate of 9% with end year discounting.
3. No inter crop type transfers are permitted. This is because all the crop types, except the general yield one, represent individual stands.
4. All replanting is into the general yield crop type.
5. There is no replanting into or out of bareland, so that the system is closed with respect to area flows.
6. The minimum age of clearfelling is 25 years, and the maximum age of clearfelling is 36 years for all crop types.
7. Harvest flow constraints are capacity based, reflecting firm and forecasted supply commitments. The capacities in the various periods were set at the levels below, with the structure of these designed to allow for downgrading, if required.

(a) Period 1

- Pruned Material: $\geq 26\,000\text{ m}^3$
- Pruned + Sawlog 1: $\geq 62\,900\text{ m}^3$
- Pruned + Sawlog 1 + sawlog 2: $\geq 149\,500\text{ m}^3$
- Total production: $\leq 177\,000\text{ m}^3$

Table 4.4: Harvest schedule by crop type for the first ten years of the medium term tactical plan

Period	Harvest Schedule by crop type (ha)										TOTAL
	A	B	C	D	E	F	G	H	I	Y	
1							101.3	105.0			206.3
2						167.3	45.7				213.0
3				2.6		53.7			192		248.4
4				37.4	170.7						208.1
5			109.8		41.3						141.1
6			106.2								106.2
7		170.0									170.0
8		192.0									192.0
9										181.2	229.0
10	71.0									40.8	71.0

(b) Period 2–3 (levels are annual)

- Pruned Material: $\geq 24\,800\text{ m}^3$
- Pruned + Sawlog 1: $\geq 67\,600\text{ m}^3$
- Pruned + Sawlog 1 + sawlog 2: $\geq 157\,600\text{ m}^3$
- Total Volume production: $\leq 185\,000\text{ m}^3$

(c) In the remaining periods (4–60), smoothing constraints are imposed that restrict the total volume harvest to fluctuate by no more than 30% from the level in the previous period.

Figure 4.1 shows the level of volume cuts for the first 30 periods of the horizon by both total volume, and its breakdown into log assortments. The detailed results showing the levels of harvests, the revenues, costs, replantings, and other details of the solution are given in Appendix B. Table 4.4 shows the area, by stand, scheduled for harvest over the first ten years of the plan. In that table, stand Y refers to the general yield crop type.

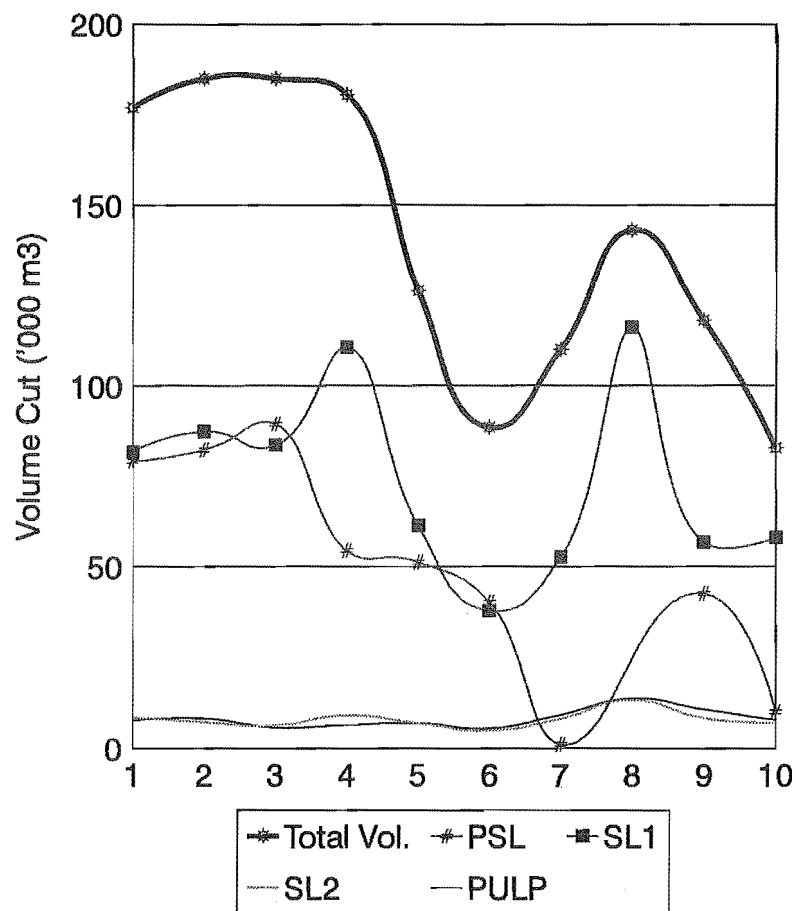


Figure 4.1: Harvest schedule (m^3) by quality class for the first ten periods of the medium term plan

4.5 The short term tactical model

The aim of the modelling at the short term tactical level is to disaggregate the medium term tactical plan to detailed annual and even lower levels; to determine short term merchandising strategies by providing preliminary, detailed log production plans at the setting or group of setting level, and; to optimize the location and construction of roads and landings. This last aspect of the short term tactical model is not addressed in this case study, because a model suitable for performing the evaluation was not available. The details of the issues which would be addressed with this aspect of such a model are described in section ??, and such a model was not developed as part of this study, due to limitations of time. The log merchandising objectives of this level are, however, addressed comprehensively for the case study. In the absence of such a model, this level was modelled with the FOLPI system, the major features of the package of which have already been described above.

The model developed in FOLPI at this level is intended to disaggregate the first three years of the medium term tactical plan into more detailed plans with quarterly horizons. A total of 667.7 ha of the estate is scheduled for harvest in the first three years of the medium term horizon, and the short term tactical model is intended to provide a more detailed harvest plan for the case study. The yield tables used in the development of this level model are shown in Appendix B, and comprise the yield data from the first three years of the medium term plan for stands D, F, G, H, and I. The annual volume increment within each of the periods at the medium term level was distributed uniformly over the four periods that comprise each period of the higher level. The constraints used to control the modelling, and other features of the model at this level are listed below.

1. Objective function is to minimize the costs of wood supply, including those of harvesting.
2. The planning horizon is twelve periods, each one quarter in length.
3. A basic assumption in FOLPI is that a crop type is clearfelled, regenerated, and can then be cut after achieving the minimum clearfell age, if this falls within the horizon. There is a danger of obtaining meaningless results if such short term horizons are modelled with the system, which is designed for modelling much longer term problems. Because FOLPI is designed for modelling horizons divided into periods

Table 4.5: Minimum capacity levels for the short term tactical model

Period	Volume by Quality Class (m ³)				TOTAL
	PSL	SL1	SL2	PULP	
1	8 400	11 100	22 700	6 800	49 000
2	5 200	9 400	19 000	6 800	40 400
3	6 200	9 700	20 200	6 800	42 900
4	6 200	9 700	21 700	6 800	44 000
5–12	6 200	10 700	22 500	6 800	46 200

of at least a year, when it is used in modelling such horizons, some of the crop types can undergo a harvest, regeneration, and possibly another harvest within this period. Such a result would clearly be meaningless, as the horizon is too short for this to occur in practice. In this case, regeneration was permitted only into the dummy bareland crop type, which has the effect of taking the area out of production and eliminates such a possibility.

4. Minimum clearfelling ages are set at period zero.
5. For stands with area below the minimum age of clearfelling, the entry of these in the yield tables are in the period that corresponds to that at which they would have achieved this age.
6. Regulatory constraints are capacity based, reflecting levels of firm and projected supply commitments. The capacities are set at the levels in Table 4.5, by period and log quality class. The harvest schedule for all periods in the horizon are shown in Table 4.6, with 7.4 ha of the area scheduled for harvest over these periods by the medium term plan left uncut. Detailed FOLPI outputs of the plan at this level are shown in Appendix B

4.6 The Operational Scheduling Model

The main objective at this level is to develop a detailed harvest schedule and log production plan for the stands scheduled for harvest in the first period of the short term tactical plan, for operational implementation. The horizon is one quarter, which is divided into

Table 4.6: Harvest schedule by of the short term tactical plan

Period	Stand Harvest Schedule (ha)					TOTAL
	D	F	G	H	I	
1			39.2		20.2	59.6
2		48.0				48.0
3		51.0				51.0
4		52.7				52.7
5					64.0	64.0
6					63.6	63.9
7	3.0	13.2			44.2	63.6
8		52.9				52.9
9		3.2		50.2		53.4
10				54.1		54.1
11			50.2			50.2
12			50.1			50.1

13 weekly periods. The log production problem can be described as that of determining how much of each stand to harvest in each period, by which crews, the mix of log assortments to produce, what volume of each log type to produce from each stand and in which period, and the markets to which to allocate the material to maximize revenues.

The specific problem here involves scheduling harvest of the two stands G and I, with the areas under each, yields by quality classes, and harvesting costs shown in Table 4.7. The market demand by period for all the log assortments are shown in Table 4.8. There are two product categories in the table, logs for the domestic and export markets. Demand for all the export material are fixed, while those for the domestic market have either simple lower bound, or both an upper and lower bound. The second line in each period for all domestic products in the table indicates the upper bound on demand for the product in the period, except where there is no upper bound, in which case there is no entry.

Export logs can be stored for only limited periods at the wharf, due to potential damage by sapstain and other wood deteriorating agents. In this problem, all export material can be stored for a maximum of eight periods at a cost of \$ 2.0 per m³ per period. Logs for the domestic market are delivered directly to mills, and storage costs for these are therefore not considered within the log production system.

There are 3 crews available, each with different productivity and costs. The crews have productivity of 2 300, 3 000, and 4 000 m³ per week respectively, and the crews have fixed

Table 4.7: Area, yields and harvesting costs of each stand for the quarterly log allocation plan

Stand	Area (ha)	Harv. Cost (\$/ha)	Yield (m^3/ha) by Classes			
			PSL	S1	S2	Pulp
I	20.2	9191	352	313	24	18
G	39.3	11466	387	413	50	32

operating costs of \$ 700.00, \$ 800.00, and \$ 1,000.00 per period, and crew/machinery relocation costs of \$ 3,100.00, \$ 4,000.00, and \$ 5,000.00, which is charged whenever a crew is moved into a stand if the same crew was not in that stand in the previous period.

A mixed integer formulation of this problem was generated with the Prolog program described in section 3.4.5, and solved with the CPLEX¹ mathematical programming package. The resulting model has 464 rows and 1 492 columns, of which 156 are integer, it has 4 141 non-zero values, and a density of 0.006. The model was solved on an IBM² compatible personal computer with a 33 MHz 80486 processor and 8 Megabytes of RAM, and optimality was proved in 70.63 seconds. The gap between the integer relaxation and the integer optimal objective value was under 0.01%, which shows that the integer relaxation is a very tight formulation of the integer constrained problem. The log production plan and crew schedules from the model are shown in Table 4.9.

To demonstrate the goal programming extensions of the operational scheduling formulation, the problem was made infeasible by increasing the demand for Pruned Sawlogs to 950 m^3 for periods 1–8, increasing the lower bound on pulpwood production to 1 500 m^3 for all 13 periods, and by making crew 3 unavailable. Under this scenario, the problem becomes infeasible unless extra resources are made available. The minimum levels of such resources required are determined by running the model with the objective of minimizing the cost of supplying these, and Tables 4.10 and 4.11 shows the results of this. Penalty costs, and not the activity levels of the external resources, are used in this case in order to make the objective function uniform in units. The results of this show that extra crew capacity capable of harvesting 2 000 m^3 in stand A and 2 800 m^3 in stand B is required in the first period to make the problem feasible. On the resource side, there is a deficit of more than 1 000 m^3 of pulpwood in all the periods between 1 to 10, except in periods 4 and 6.

¹Registered Trade Mark

²Registered Trade Mark IBM Corp., USA

Table 4.8: Market Demand By Product and period for the operational scheduling problem

Period (Week)	Demand By Product (m ³) and Log Type							
	Export Logs					Domestic Logs		
	PSL	JpA	JpJ	Kor	Chn	S1	S2	Plp
1	370	1 600	850	1 450	1 400	350	300	1 100
2	370					350	2 000 300	1 100
3	370			1 600	1 300	350	2 000 300	1 100
4	370					350	2 000 300	1 100
5	370					350	2 000 300	1 100
6	370	1 600	1 600			350	2 000 300	1 100
7	370	1 600	1 600	2 200		350	2 000 300	1 100
8	370					350	2 000 300	1 100
9	800					350	2 000 300	1 100
10	800					350	2 000 300	1 100
11	370					350	2 000 300	1 100
12	370	2 000	950	950	950	350	2 000 300	1 100
13	370					350	2 000 300	1 100

A goal programming model of this problem was then formulated with the goals and following the formulation described in Chapter 3. In this example, all the goals were given equal weights. Tables 4.9, 4.10, and 4.12 show the log production plan, harvest schedule, and crew allocations for the base case, minimizing cost of external resources, and of the GP models respectively.

Tables 4.11 and 4.13 shows the levels of slack production for all the log types and crew allocations in all the periods. There is an almost equivalent level of slack in crew allocations between the two models, of about 4 800 m³ for both the GP and the cost minimizing models. However, there is a much greater slack in production of pulpwood in the model formulated to minimize the cost of extra resources than the GP one. This is probably a function of extra production in the GP model, which result from the model attempting to maximize marginal revenue from the extra production as a means of achieving the targets of the revenue maximizing goal. Since such extra production contributes nothing to the objective value of the extra cost minimizing, there is no such production.

In the base case, there is no storage in the log allocation plan. In the model with the objective function of minimizing the cost of using external resources, there is a large quantity of storage of products in the solution, with a total of 37 120 m³ - periods of storage, which is much higher than the levels in the MINMAX model. There is a limited amount of storage in the GP model, amounting to a total of only 1 002 m³ - periods, which is less than 3% of that in the second model. This indicates that it is probably more economical to store material, other than to relocate crews into different stands between periods, unless minimization of storage is a primary goal.

The level of achievement of the goals are as follows:

- Goal 1: Maximizing net revenues is fully achieved.
- Goal 2: Minimizing cost of external resources: goal is also fully achieved.
- Goal 3: Minimize total costs: this goal is not fully achieved, with a deviation of 0.17%, which is equivalent to a total cost of \$ 5,172.00.

Table 4.9: Log production Plan for the Base Case of the Quarterly log Allocation Model

Stand& Period	Area Cut	Production by log type (m³)								Crew Allocated
		PSL	JpA	SL1	JpJ	SL2	Kor	Chn	Plp	
Period 1										
A	4.55	370	1 600			300			948	1
B	4.76			350	850		1 450	1 450	152	3
Period 2										
A	1.08	370		350		26			19	1
B	1.54					274			1 081	3
Period 3										
A	1.44			350		300		343	26	1
B	4.54	370					1 500	1 600	1 074	3
Period 4										
A										1
B	2.4	370		350		300			1 100	3
Period 5										
A										1
B	2.4	370		350		300			1 100	3
Period 6										
A	4.24	370			1 315	300			1 016	1
B	2.63		1 600	350	285				84	3
Period 7										
A	2.71	370		350		300			899	1
B	4.54				1 600		2 200	2 200	201	3
Period 8										
A										1
B	2.64	370		558		300			1 100	3
Period 9										
A	1.97	692	6 166	616		47			35	1
B	1.62	108				253			1 065	3
Period 10										
A										1
B	2.89	800		350		300			1 100	3
Period 11										
A										1
B	2.4	370		350		300			1 100	3
Period 12										
A	4.2	370	2 000						599	1
B	4.54			350	950	300	950	950	501	3
Period 13										
A										
B	2.4	370		350		300			1 100	3
TOTAL	59.49	5 670	5 816	5 024	5 000	3 900	6 100	6 543	14 300	

Table 4.10: Log production Plan for the Cost minimizing Objective of the Quarterly log Allocation Model

Stand& Period	Area Cut	Production by log type (m ³)								Crews Allocated
		PSL	JpA	SL1	JpJ	SL2	Kor	Chn	Plp	
A	8.6	950	663	350	791	300	1 450	1 400	154	1,2
B	1.2		937		59				37	
Period 2										
A	2.5	891	792						106	1
B	2.6	1 009	617	350		300	558		83	2
Period 3										
A	4.2	846		350		300		1 250	254	1
B	2.6		617				1 600		83	2
Period 4										
A	3.2			350			501		1 416	1
B	2.6	1 009	751			300	157		83	2
Period 5										
A	1.2									
B	6	2 326		350	2 133	300			192	1,2
Period 6										
A	0.4					300			8	2
B	3.4	91		350	1 067				1 492	1
Period 7										
A	1.2	427		350		59			22	1
B	2.6				491	241	1 485		83	2
Period 8										
A										
B	2.6	1 009	558	350		300			83	1
Period 9										
A										
B	2.6	1 009		350	459	300		99	83	2
Period 10										
A										
B	3.4	370	32	350		300	450		1 500	1
Period 11										
A										
B	3.4			350		300		851	1 500	1
Period 12										
A										
B	3.4		850	350		300			1 500	1
Period 13										
A										
B	2.9	370		350		300			1 500	1
TOTAL	60.6	10 307	5 817	4 550	5 000	3 900	6 201	3 600	19 496	

Table 4.11: Slack in log production and crew allocation for the Cost minimizing objective of the Quarterly log Allocation Model

Stand& Period	Area Cut	Slack Production by log type (m ³)								Crew Allocation
		PSL	JpA	SL1	JpJ	SL2	Kor	Chn	Plp	
1									1 308	4 800
2									1 310	
3									1 162	
4										
5									1 308	
6										
7									1 395	
8									1 417	
9									1 417	
10										
11										
12										
13										
TOTAL									9 317	4 800

4.7 Controlling Log Outturn

The system which was developed for controlling outturn involves the iterative revision of SED specifications and selected quality features for all the log types. To illustrate the method, it was implemented for the log production plan for the first period of the operational plan for both two stands, following the procedure described in section 3.4.7. The first period was selected, because the log production plans for both stands contain a mix of both domestic and export log types. It has usually been the case that the fixed length grades that are typical of export log types are much more difficult to model than random length domestic grades. Their inclusion in this example, therefore, can serve as an illustration of the flexibility, or lack there-of, of the proposed system. An added complication of export material, is the requirement of an average SED specification for every shipment.

The new, revised specifications for the different stands and periods are presented in Table 4.14. Figure 4.2 and 4.3 show how the SED and volume yield for one log type progressively approaches the target volume, with the determination of a new minimum SED at every iteration of the bisection method. Table 4.14 also shows the level of achievement of volumes from the quarterly log production plans for each log assortment, using the new specifications. From the table, it can be seen that the log production targets are achieved

Table 4.12: Log production Plan for the GP Quarterly log Allocation Model

Stand& Period	Area Cut	Production by log type (m ³)								Crew Allocated
		PSL	JpA	SL1	JpJ	SL2	Kor	Chn	Plp	
Period 1										
A	5.5		1600	350	850		1 009		100	2
B	3.6	950				300	441	1 400	116	1
Period 2										
A	0.14	49				47	412		3	2
B	3.4	901		350		253			1 497	1
Period 3										
A	2.3	796		350					41	2
B	3.4	154				300	1 188	1 188	109	1
Period 4										
A	0.5			350					22	2
B	2.7	950				300			1 135	1
Period 5										
A										2
B	2.5	950		350		300			565	1
Period 6										
A	3.3		1 600	350	26				59	2
B	3.4	950			1 574	300			177	1
Period 7										
A	3.3	950					1 292		59	2
B	3.4			350	1 334	300	908	908	109	1
Period 8										
A	0.14	49		44		3			3	2
B	3.4	901		306		297			1 497	1
Period 9										
A										2
B	3.3	800		350		300			1 500	1
Period 10										
A										2
B	3.3	800		350		300			1 500	1
Period 11										
A	0.4	127		113					6	2
B	3.4	370		237		300			1 493	1
Period 12										
A	3.3	243	1 400						59	2
B	3.4			350	342	300	950	950	109	1
Period 13										
A	1.5	370		350		300			27	2
B										1
TOTAL	60	10 310	4 600	4 550	4 126	3 900	6 200	4 446	16 695	

Table 4.13: Slack in log production and crew allocation for the GP Quarterly log Allocation Model

Stand& Period	Area Cut	Slack Production by log type (m^3)							Crew Allocation
		PSL	JpA	SL1	JpJ	SL2	Kor	Chn	Plp
1									1 284
2									
3									1 350
4									343
5									934
6									1 265
7									1 333
8									
9									
10									
11									
12									
13									
TOTAL									6 509

to a large extent with the new specifications, within an acceptable tolerance for most of the stands. The average SED for all is also better than the specification for all but one log type.

The two exceptions to volume target achievements are for SL2 and Pulp in Stand A. The relatively large level of over-achievement for the two log types is probably a reflection of the very low levels of the targets, which causes any small absolute deviation to appear quite large when expressed as a relative proportion of the target. It can be expected, though, that with larger volume targets, the proportionate level of achievement when using the outturn control method is likely to be within a 5% tolerance. Further implications of using the outturn control method, and of the planning system as a whole, are discussed in greater detail in the next chapter.

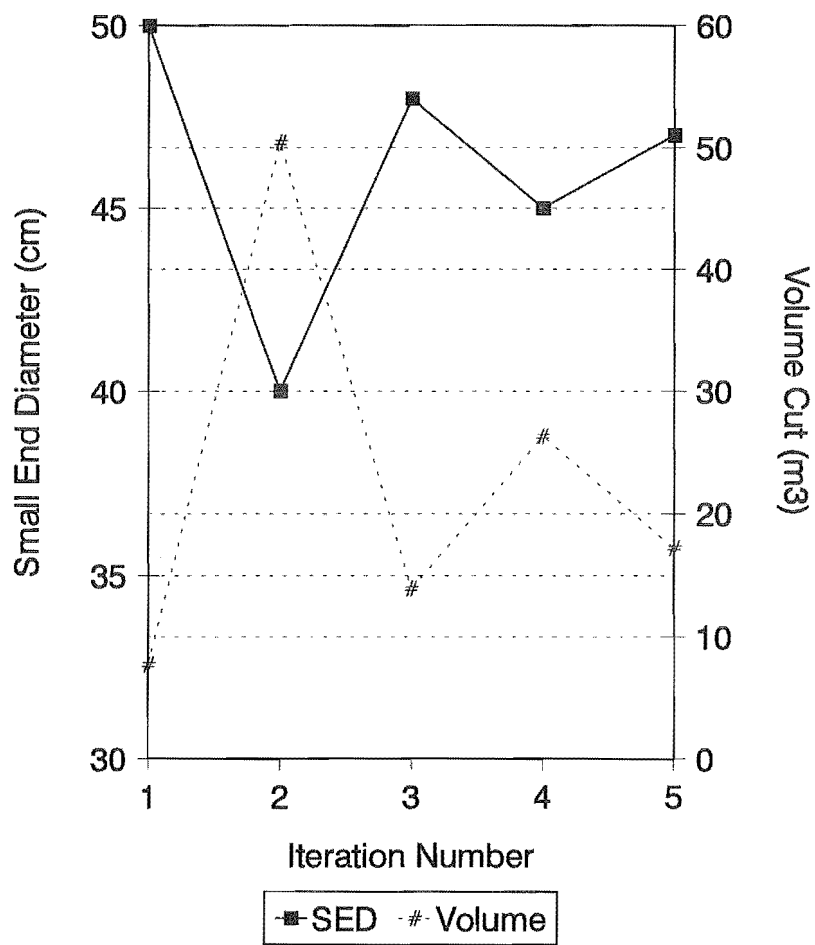


Figure 4.2: Example 1: change in volume cut with iterations of the bisection procedure

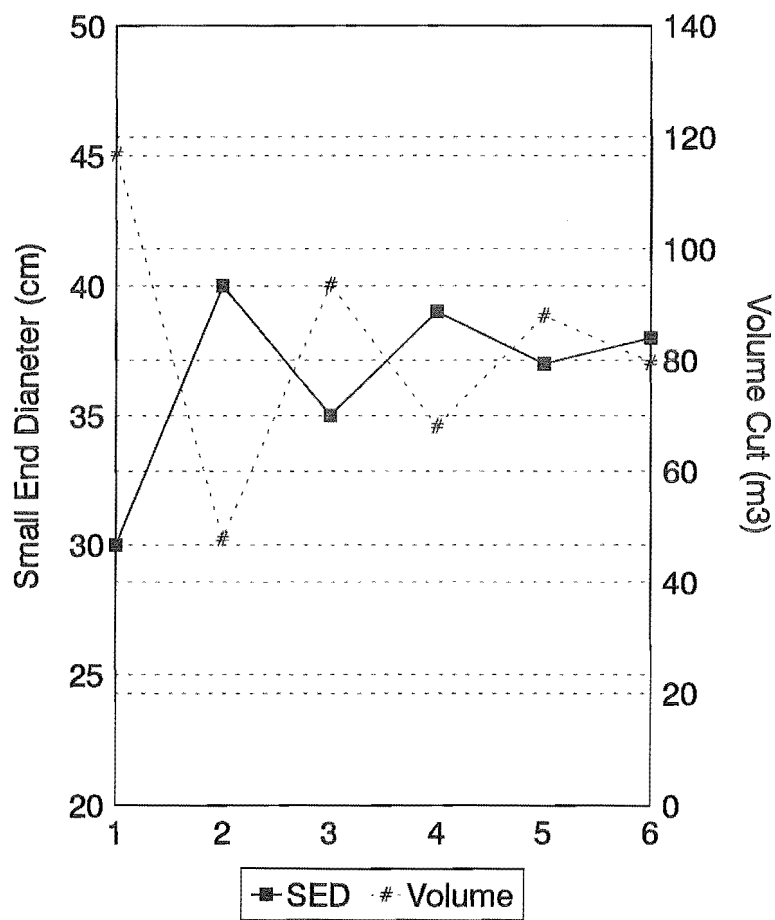


Figure 4.3: Example 2: change in SED and volume cut with iterations of the bisection procedure

Table 4.14: Example 1: Revised log specifications and volume achievements for log assortments from stand A in the quarterly log production plan

Period & Stand	Log Grade	minimum specs.	Revised specs.	Production Plan	Volume Achieved	Deviation from target
A, 1	PSL	Length: 3-8	5.5-8	370	355	-3.2%
		SED: 30	46.5			
		Ave. SED	48.7			
	JpA	Length: 4,8,10,12	8,10,12	1 600	1 654	+3.6%
		SED: 20	46.5			
		Ave. SED: 34	36			
	SL2	Length: 3-6	6	300	494	+65%
		SED: 20	35			
		Ave. SED: none	35			
	PULP	Length: 3-12	6	300	494	+65%
		SED: 10	10			
		Ave. SED: none	16			
B, 1	SL1	Length: 3-6	6	350	346	-3.2%
		SED: 20	46			
		Ave. SED: none	48			
	JpJ	Length: 4,8,10,12	8,10,12	850	876	+3.6%
		SED: 20	37			
		Ave. SED: 26-28	38.5			
	Kor	Length: 4,5,7,11	4,5,7,11	1 450	1 443	-0.5%
		SED: 20	34.5			
		Ave. SED: 26	38.5			
	Chn	Length: 4,6,8,10	4,5,7,11	1 450	1 443	-0.5%
		SED: 14-16	16			
		Ave. SED: 25-26	24.3			
	Pulp	Length: 3-12	3-12	152	183	+ 20%
		SED: 10	10			

Chapter 5

Discussion

This study was conducted with the objective of developing a methodology for integrating the modelling of long and short term log production plans, specifically the allocation of log production to current and potential future markets. Two different aspects to such integration have been considered: one is the coordinated optimization of log production strategies over multiple stands, and the other is the global optimization of log merchandising strategies across short and medium term decision levels.

A hierarchical framework was developed for modelling log merchandising across temporal decision making levels, and comprises the three levels. These levels are (i) a medium term tactical model which addresses issues of medium term feasibility, sustainability and profitability of the production process; (ii) a short term tactical level which addresses issues of stand access, and disaggregates the medium term plan into annual aggregate wood logistics, and; (iii) a short term operational model for scheduling weekly log and crew allocations, and for developing detailed weekly log production plans. The models are run in a rolling horizon fashion, with the results of each level forming part of constraints to lower levels.

There are several advantages of hierarchical systems when compared to monolithic approaches to model development. The first is that such systems guarantee coordination of overall decision making, while enabling the different levels to be modelled separately. This allows characteristics particular to a decision level to be built into the corresponding model with little difficulty. This advantage is illustrated with the models for the different levels in the planning problem presented here. The modelling of the medium term

tactical plan is based on prevailing harvest scheduling technology, and all the major developments in such planning systems can be employed at this level, without affecting the formulation of the other models within the system. Similarly for the other levels of the modelling, which can assume different model forms such as simulators instead of optimizers. The only requirement of such systems is that they satisfactorily capture the major essence of the problem, and provide a set of targets and constraints for lower levels.

A related advantage of hierarchical systems is that they reduce the complexity of the decision making by partitioning the overall problem into smaller, easily manageable parts. This is also illustrated by the models at the various hierarchical levels in the structure adopted in this study. This reduction in complexity, however, may be at the expense of some acceptable weakening of the linkages between the sub-models, with resulting losses in global optimality. However, such losses are likely to be minimal, and are far outweighed by the gains in modelling simplicity.

As an example, consider if a large-scale model was to be developed that encompasses all three decision levels in this hierarchical structure. The resulting model is likely to be quite a large mixed integer LP one, with a considerably complex constraint structure. Such a model would require a substantially large and complex data set to run, and problems with intractability could be experienced with its solution. This is because of the potentially large model size, when combined with any possible integrality requirements. Kent et al. (1991) report that problems with intractability of the FORPLAN system are encountered frequently with models that attempt to integrate strategic, tactical and operational planning. The relatively simpler formulations of the models at the various levels in the hierarchical structure are much easier to develop, formulate, and solve than a corresponding monolithic model could ever be, which fact graphically illustrates the advantages of partitioning.

Murphy (1993a) estimated that by partitioning a large problem into sub-parts, overall model development and debugging time can be reduced by up to 70%. If even only a fraction of this advantage is realized as a result of such partitions, major savings in costs can still be made because model development is a labour intensive task. However, the major advantage of partitioning is likely to result from earlier availability of the models, and the greater ability by managers to understand, accept, and run the models with comparative ease. Kent et al. (1991) discuss the necessity for trade-offs between model comprehensiveness (and therefore complexity) and model understandability with respect to resource

modelling with FORPLAN. The paper quotes Irland (1985) that “... *comprehensiveness is a trap ... comprehensive planning fails to sort the strategic from the trivial, wastes resources on secondary concerns, paralyses the will in the face of complexity, and bogs down in empirical debates for lack of direction ...*”. Hierarchical systems allows comprehensiveness to be incorporated in models, while resulting in simple, understandable models at the various levels, unlike the cited FORPLAN example.

The hierarchical structure presented here also illustrates another common feature of such systems. This is that such structures mirror an organization's decision making levels, and therefore enables the decision maker to gain better insights into the modelling. Planning at the medium term tactical level is likely to be the function of top and middle management levels, whose concerns are mainly with the strategic positioning and sustainability of the firms wood supply potential, and with legal, environmental, and other such regulatory requirements. Similarly for the short term tactical and operational scheduling levels. These models address issues at increasingly greater detail which correspond to lower management levels, whose concerns are more with issues of implementation than of sustainability. Regulatory concerns, if any, are likely to be at an increasingly more localized level. The managers at these different levels therefore use decision support systems which are directly related to the decisions they are required to make, and as a result, have a better opportunity to gain insight into the models. In this context, Vertinsky et al. (1994) describe a disadvantage of monolithic models as being that they do not provide the level of access and transparency that must characterize such systems, for the solutions to be accepted by stakeholders to the decisions.

Planning of log merchandising is, in many respects, a stochastic problem. This is because of the long term nature of forestry projects, which implies that data at the detailed level are usually unknown or uncertain when long term decisions are made. Such uncertainties are reflected, for example, in unforeseeable changes in the resource. For example, these can result from catastrophic occurrences of fire or pests, which events can have quite dramatic effects on the resource (see, for instance, Reed and Errico (1986) and Obiri (1994)). Other changes are likely to be in market behaviour assumptions which underlie the long term decisions. Under such conditions, it is intuitively not logical to use prevailing deterministic LP approaches to harvest planning. Instead, a stochastic model, or a deterministic LP in which the more uncertain elements are represented with stochastic parameters maybe required.

An approach to consideration of stochastic parameters in a deterministic LP harvest scheduling model is reported by, for example, Reed and Errico (1986) and Leefers (1991), which latter reference reports the integration of Monte Carlo simulation within an LP. However, a major obstacle to the modelling of log merchandising with stochastic LPs is that such models tend to suffer problems of intractability (Dempster et al., 1981). Dempster et al. (1981) have shown that multi-stage hierarchical systems are a good heuristic for solving stochastic problems, and that such systems have a high probability of finding an optimal solution near to the related stochastic one. Hierarchical planning, therefore, offers a simple and effective alternative modelling approach for taking into account the stochastic elements of log merchandising problems, which advantage does not hold for monolithic modelling approaches.

The other aspect to integration, is that of log merchandising planning over an entire estate, which aspect has received far much less attention. Methods that have been used include developing specific cutting strategies for a stand, and the function of the log allocation model is then one of scheduling stand harvest, and of allocating the generated logs to markets. A single cutting strategy (for example Deadman and Goulding, 1979), or a limited set of strategies for each stand (for example, see Hay and Dahl (1984) and Smith and Harrel (1961)) may be developed. In the latter case, a further function of the allocation model is to determine the area of a stand in which to apply a selected cutting strategy. This method is limited by the large number of potential strategies, of which only a few can be included. It can also not be determined if the selected ones include the potentially optimal strategy. These approaches unnecessarily constrain the potential log mixes in production plans. Therefore, while such log mixes may be feasible, they are frequently not optimal.

Another approach involves iterative development of new strategies that improve a previous feasible solution. The changes in log mixes are usually driven by log values, and the log allocation part may be modelled by an LP model which indicates the optimality of the log mixes (Eng et al., 1986; Eng, 1982; Maness and Adams, 1991; Mendoza and Bare, 1986), or limits maybe heuristically imposed on the production of certain log types (Sessions, Olsen and Garland, 1989; Murphy, 1993b). The drawback to use of the former method is the vast computational resources it requires. These modelling system are also complex, and requires to be run by specialised technical personnel. The other reported systems have the drawback that they do not provide globally optimal solutions. Another disadvantage with such systems is that it is usually possible to take into consideration only one or a few constraints on production, which is unrealistic for practical, planning.

The approach adopted here, which combines a system for describing potential yield of a stand, and separate outturn optimization and control systems, has several advantages over the methods already described. The first is that the stem quality classes and log values used to describe yields, are not affected by other than major changes in log mixes supplied to markets, and are unaffected by log values. The stem quality classes are also, comparatively, more stable than market log types. Consequently, new yield estimates are not required, unless major changes in market demand eventuate. This is as opposed to the method of determining outturn to market log grades, which approach may require new yield estimates whenever there significant changes in planned log mixes. The approach proposed here, therefore, offers a more robust yield description system. From experience with this modelling approach, it can be argued that adoption of a standard system of stem quality classification for describing yield of the standing crop within an organization, such as the aggregated log quality classes proposed by the New Zealand Conversion Planning Conference (Whiteside and Manley, 1986), has much to recommend it.

Outturn optimization, in this system, is a function of the log allocation components of the medium, short, and operational LP models. Log production plans are developed by disaggregating the stem quality classes from the yield description into the marketable log types, with downgrading employed as a marketing strategy. The advantage of this system is that log production plans can be developed in a computationally simple, flexible, and feasible manner. The system does not require the large computational overheads of column generation techniques, such as those of Eng et al. (1986), Maness and Adams (1991), and Mendoza and Bare (1986), for instance, while providing greater flexibility in the generation of log mix production plans than systems based on outturn assessment to market log types.

This approach can yield even better log mix plans than column generation techniques under some conditions. One such condition, for instance, is if a plan calls for cutting two or more log types which have fairly similar quality requirements (for example, Japanese J, Chinese, and Korean grades in Table 4.2) from the same stand and period. With the column generation technique, and indeed in other system where changes in log mixes are driven by log values, such a log mix solution can sometimes be impossible to obtain. This is because the bucking model always cuts the log type with the highest value in any iteration, at the expense of the rest with similar quality requirements from which to choose. In such a case, the log types can be cut either from different stands in that period, or from the same stands but in different periods. The fact that it is also not possible to downgrade

and change log specifications in the column generation technique, which is a frequent operational practice, again shows the added flexibility of the approach here.

With the method developed in this study, generation of log mix production plans is the function of an LP knapsack formulation. Johnston (1990) cited as an advantage for the use of LP in cutting stock (or knapsack) problems, the fact that such models are very efficient and flexible in resource allocation, and for reducing waste. The other advantages of LPs in this context include the fact that solutions can be constrained by many factors crucial to the production process, which can be very difficult to model with other planning techniques. However, Johnston (1990) also cites, as related disadvantages of LPs, that in rounding continuous solutions to integer ones: (i) the rounded solutions may produce quantities outside the accepted tolerances; (ii) that cutting patterns with low usage remain in the solution and cause difficulties in practical scheduling of manufacture, and; (iii) that an excessive number of cutting patterns can remain in the solution.

The first disadvantage is crucial to the multiple stem bucking problem, and is the function of the system for controlling outturn presented and discussed in section 3.4.7. The procedure has the function of reducing deviations to within acceptable tolerances, and is discussed in greater detail below. The second problem is not as serious in the stem bucking problem as it is in actual manufacturing settings, which may require separate machinery setups for each batch produced. However, the model presented in section 3.4.5 lessens this problem to some extent, as the log allocation system discourages production plans involving small batches by imposing setup costs through crew relocation costs.

Experiences with application of the outturn planning methodology to the case study suggest that the last problem is only minimally experienced with the outturn planning methodology presented here, as compared to the MARVL approach (Deadman and Goulding, 1979), for instance. This is because the flexibility in planning log mixes provided by the LP allows more efficient targeting of log production to particular logging settings or stands in a period, as a function of market demand, prices, and logging costs. For instance, plans for both stands in period 12 of the case study results presented in Table 4.9 has the largest number of log types produced in any period. But these are only seven out of the possible ten, with the production of the remaining log types allocated to the other stands. If the MARVL approach was used, the bucking evaluation would be done with all possible log types for both stands in the period, which could result in plans requiring the cutting of all the log types in both stands in that period. Of these, it is highly likely that the production

requirements for some of the log types would involve small volumes. The LP approach as used here is definitely an improvement in this respect.

The outturn control method is the last component in the outturn assessment system developed in this study. There have traditionally been few systems for outturn assessment that include a component for outturn control in the published literature. In this regard, most of the outturn assessment systems can be described as being descriptive, in the sense that they provide a description of what mix of logs to cut from a stand in a period, but do not provide a mechanism for realizing these targets in field bucking, which is a stem by stem process. This is as opposed to systems which provide not only a solution of the log mixes to cut, but also specific guidelines which, if followed, leads to the realization of such targets. Examples of the former include most systems based on outturn assessment to market log types, such as Sessions, Olsen and Garland (1989) and Deadman and Goulding (1979), while examples of the latter category include the approaches of Murphy (1993b) (cited in Goulding (1993)) and Eng et al. (1986).

In the system described by Murphy (1993b), this is accomplished by revising log specification variables using a search strategy, while in Eng et al. (1986) the control is in the form of classification of stems into two way quality and size classes. In the latter approach, the solution provided by the optimization system is then the number of stems in each class on which to apply specified strategies. The approach of Murphy (1993b) has the drawback that it is not an optimizing model, and requires that a separate model be implemented for each stand and period. The method of Eng et al. (1986) suffers from the unwieldy number of stem quality and size classes, which makes it impractical for routine use. The approach adopted here overcomes the drawbacks of the two systems, in being simple and is aimed at finding specification variables that yield an optimal log mix. The method also has the advantage that it can be used to manipulate average SED and lengths, which is not possible with the other approaches. As average SED is one of the specification variables for export material, this can provide managers with greater capability to improve batch quality by reducing variability of logs within a shipment.

However, the method could be improved further, by development of more efficient mechanisms for selecting and modifying log specification variables. The method of bisection, which drives the revision, requires several iterations of the DP bucking evaluation in order to achieve target volumes, which can have significant demands on computer time for sizeable samples. This could be improved by development of more efficient heuristics for

selecting and generating new specifications. These can be implemented in the form of expert intervention between iterations, as a mechanism for establishing values for variables that yield target volumes in a more intuitive and faster way. Knowledge based programming could offer one possible avenue for implementation of such heuristics.

A solution that cannot be provided by the outturn assessment system developed in this study at present, is the capability to plan log batches that have a proportion of the total volume in specified lengths by log types. Export log specification frequently have constraints on the composition of a log shipment, by proportion in certain lengths for each grade. Donnelly and Whyte (1994) discusses this aspect of export log specifications in great detail. The outturn assessment method proposed here solves the total volume of the log types supplied, but not its composition by lengths. The outturn control system can be used to constrain the lengths of a log assortment by manipulating its length specifications, but this is possible only to a limited extent. Such an extension can enhance the utility of this methodology to facilitate a crucial facet of log production plans, which has not been addressed at all in the published literature. However, the method developed here can form a useful base for the development of such a system.

The results of the case study demonstrate the potential of using the planning system for modelling log merchandising, and also illustrates some of the features and advantages of the approach. The medium term tactical model was developed with the FOLPI harvest scheduling package (Garcia, 1984). The model form here is similar to the many harvest scheduling models in the published literature. Regulatory concerns and other issues can be incorporated into the model here, with only little consideration given to the lower level models, except in the form of capacity or flow constraints, because of the modularity.

The short term tactical model was also developed in FOLPI for the case study, because of a lack of a suitable model that could address the issues of concern at this level. The system described by Dykstra and Riggs (1976) goes some way towards addressing some of the issues at this level, and could form a basis for the development of such a system, but it would require further extension to cover log merchandising issues. However, if the log production planning system developed in this study was used, then the inclusion of this technique within that model would offer no conceptual difficulties. A system most likely to be able to address the issues of concern at this level would be composed of a mixed integer LP, with the data on potential landing and road locations generated from a Geographical Information System (GIS), and would be interfaced to a stand record Database

Management System (DBMS), in which inventory, yield, and other pertinent data for each stand are stored.

Modelling systems that integrate these components for forest planning are increasingly appearing in the literature; for instance, Whittaker and Brown (1991) have integrated a DBMS to an LP, in which the coefficients of the LP are extracted from the DBMS, from data previously entered as part of routine management, in an application in the meat industry. Davis and Martell (1993), Lappi et al. (1994), and Vertinsky et al. (1994) have recently reported applications that integrate a GIS, a stand record DBMS, and forest estate LP and simulation models in forest planning. In these systems, the GIS is used primarily in a reporting function. However, it should be possible to extend this approach to use the GIS as the primary data entry system for geographically referenced data to an LP model.

The resulting short term model is likely to be a large MILP for problems of a realistic size, as an integer variable is required for every possible road and landing location in every period, and is also likely to have considerable special structure. Nemhauser (1994), Johnson and Nemhauser (1992), and Barnhart et al. (1993) report the successful solving of MILP applications with several thousand integer variables on commercial packages, which indicate that the short term tactical model could also be similarly solved. However, special purpose heuristics for reducing problem size and for solving such problems, or both, which exploit problem dependent structure, may be required. This is because of potential problems with model intractability, due to the large model size and integer constraints. The solution strategy reported by Dykstra and Riggs (1976), and the heuristics discussed by (Barnhart et al., 1993; Nemhauser, 1994; Johnson and Nemhauser, 1992; Rosenthal, 1994) offer useful starting avenues for research.

The quarterly operational scheduling model was modelled with the formulation developed as part of this study. The integer relaxation of this model is a very tight formulation of the related integer constrained one, as is shown by the very small gap between the continuous and integer optimal objective values. In the case study, this gap is very small, at under 0.1%. The problem was solved within a very reasonable time of 70 seconds, with the CPLEX mathematical programming package. However, the solution time can be expected to be significantly higher for problems of a realistic size. However, the fact that the difference between the continuous and integer optimal solutions is very small, is an indication that the problem could be solved to near optimality with heuristics based on approximation techniques, such as the one reported by Rosenthal (1994).

Some other useful information that could be obtained from the operational model is that of establishing a resource, demand, and harvesting system constrained value of the various log types. Currently, this function is limited by the integer constraints in the formulation. A fruitful line of investigation might be how such information could be obtained from this formulation, and how such information is affected by the integrality restrictions.

The results of the case indicate the feasibility of using the modelling system for multiple period problems. In the case study, results from the medium term model, in terms of area by stand harvests, are disaggregated by the short term tactical model. No problems with infeasibility are encountered at this level, because of the capacity constraints imposed at the medium term tactical model. Similarly, the short term tactical solution is further disaggregated into implementable, operational log production plans for each stand, as constrained by availability of harvesting systems. Again, no infeasibilities are encountered, due to the linking of the two models with capacity constraints at the higher level model. The modelling is at increasingly detailed resolutions, with new activity variables and constraints incorporated at each decision level to reflect the issues of specific concern at the levels, which illustrates the flexibility of hierarchical planning systems.

The alternative GP formulation of the operational problem can be used to model multiple, conflicting objectives, and for dealing with infeasibilities, as demonstrated in the case study. In the example GP model in the case study, only a few of the possible objectives are modelled. However, these result in different production plans. A good example is in the quantity of storage in the infeasible multiple objective case, where the total level of storage is only 3% of the equivalent level in the cost minimizing model. The level of storage probably reflects the effects of trade-offs in crew movement and storage costs, and this demonstrates the potential of the GP formulation for exploring the effects of various factors in the log production process.

The differences in log production and crew allocation plans, especially of the slack production of pulpwood over the horizon, also serves to demonstrate the effects of conflicting objectives. Operational decisions are frequently made under multiple, conflicting and sometimes seemingly irreconcilable concerns. The method demonstrated here therefore offers greater flexibility in the evaluation of multiple objectives at the operational level, over single objective deterministic LP based approaches to operational harvest planning.

The major test of the system is whether it provides a mechanism for generating optimal

log production plans constrained by demand and characteristics of the resource in a flexible manner, and if such plans are indeed feasible. The log production plans from the operational model indicate the flexibility with which new plans can be developed. For each stand, the log production plan can be quite different from one period to the next, depending on market demand and the level of wharf storage.

The feasibility of the plans is demonstrated by the results of the outturn control method applied to the log production plans. In the case study, the revised SED specifications were determined to the nearest centimetre. Even then, the production plans for most of the log types are realized to within 5% of the target, even for the usually much more difficult to model fixed length grades. Furthermore, the average SED for all the log types were all above the minimum specifications, except for one log type in the reported examples. Even for this log type, the deviation from the target is only -0.5 cm. However, this could probably have been achieved too, if the SED were to be determined to the nearest 5 mm. This level of precision, however, probably has little significance from an implementation standpoint.

An advantage of this approach of outturn control, is that it leads to plans that yield log batches that are fairly uniform in size and quality features, as such features are more restricted in range. It should be noted, however, that managers may not be entirely satisfied with a mix of log types in which the less valuable material are shorter, and have lower SEDs than the more valuable material. This issue might require further investigation, and other heuristics for moderating such effects maybe required. In such cases, though, the major uses of the system could still be in developing indicative log mixes and specifications for implementing these, which a manager can then modify to suit their preferences.

A limitation of this methodology is that it cannot be used to generate specifications for log shipments in which proportions of the total volume is required in specified lengths as discussed in Donnelly and Whyte (1994). Except for the non optimizing approaches reported by Murphy (1993b) and Sessions, Layton and Guangda (1989), no other planning methodologies in the literature can provide a solution to this problem. A potentially fruitful approach to investigate as a means of solving optimal problems of this kind may be as a knapsack problem in three dimensions, such as the applications of Maness and Adams (1991) and Reinders (1993). In such a case, the total supply of log sorts could be modelled in the second dimension of the problem, while the third dimension considers the composition of such assortments by lengths. This possibility, however, was not investigated in

this study.

A major problem with mathematical programs with a modelling structure such as the one adopted in this study, is the difficulty in data preparation and entry, problem formulation, and in interpretation of resulting solutions, i.e the problem of user friendliness. This is an issue that concern many developers of mathematical programming systems, as it can frequently determine the level to which such systems are adopted by managers. This concern has been highlighted recently by, for example Whyte (1991), Dykstra (1990), and Garcia (1990). Various approaches have been attempted as a means of overcoming this limitation. One line of research has focused mainly on developing model representation schemes that facilitate model formulation and debugging (Murphy, 1992; Bodily, 1986), while another line of research has concentrated on model generation systems (Fourer, 1983). It can be argued that these issues are of concern to developers of forest planning decision support systems and does affect the productivity of such efforts. However, they are not the principal deterrents to acceptance of such systems by managers, but instead the problem is mainly in the complexity of the data preparation and entry phases of the modelling, and in translation of the resulting solution back into a form that managers can make use of. The mechanics of problem generation and model representation can be safely hidden away from users of such models, and thus become of no consequence from the managers standpoint, although it would still be a major concern to model developers.

This last facet of the user friendliness issue has been gaining increasing attention; examples include the work of Davis and Martell (1993) and Whittaker and Brown (1991). The recent development of mathematical programming systems on electronic spreadsheets and the increasingly wide acceptance of such systems is an example of a reaction to this concern. This is because spreadsheet software are widely used by managers in daily tasks, and because they are an excellent medium for data entry, reporting, and for sensitivity analysis. Forestry applications involving mathematical programming based on computer spreadsheets include those reported by Villaneuva (1992), Sicad (1993), and Leefers (1991). However, spreadsheets do have their limitations, the main one being that models developed in them have fixed structures, and are therefore not flexible for modelling problems with even moderate differences in structure, without expenditure of substantial effort. Another drawback is that any serious spreadsheet application requires use of application development command languages, or macros, but program development in macros is significantly more difficult to code and debug than conventional programming languages (Ogweno, 1988).

Stand record systems based on Database Management Systems (DBMS) are now in widespread use in the forest industry, and similarly for geographical information systems, which are used for graphical representation of the spatial relationships of forest estates. Since inventory, yield and management prescription records are already stored in such systems, it is a logical progression that systems be developed that can access such information for nominated stands, for use in formulating models of interest. It is foreseeable that the model interfaces that are likely to be most successful as data preparation and input media to mathematical programming models for forest management, are likely to integrate GIS for nominating stands for the modelling and for generating reports in a graphical form, and DBMS for generating associated stand data for the models. The approach demonstrated by Whittaker and Brown (1991) in integrating LP modelling with DBMS, and that of Davis and Martell (1993) and Vertinsky et al. (1994) in integrating LP, GIS and DBMS for modelling forest management can form a good basis for development of fully functional and integrated decision support systems.

Overall, the log merchandising system presented here offers managers a capability for evaluating log mix production plans in both the short and medium term in a flexible and simple manner, and that can be easily incorporated in current harvest planning tools. Whyte (1988) notes that forestry planning in New Zealand has tended to be resource driven, and this can be partly attributed to the lack of tools for performing evaluations between market and resource driven strategies. The yield description and outturn optimization systems developed in this study enables the evaluation of either strategy with comparative ease, and can form a useful basis for such evaluations.

Chapter 6

Summary and Conclusions

6.1 Summary

The decision on which log types to produce from a stand at time of harvesting, is often the most important in determining financial profitability of a forestry production process. The log merchandising options taken at this stage affect not only the conversion efficiency of downstream processing, but also have major impacts on developing log markets, and for regeneration of the new crop. A survey of the published literature reveals that much work has been done in the area of optimizing stem conversion, log allocation and harvest scheduling, which have yielded substantial opportunity benefits. These models, however, are usually not solved in an integrated manner, with the consequence that it is not possible to evaluate optimal trade-offs in merchandising options across short and longer term decision levels.

This study examined methodologies for the integrated planning of log merchandising over short and long term periods. Its main objective was to develop a methodology for yield description that can form the basis for evaluation of the trade-offs between stem conversion strategies, log allocation, and harvest scheduling decisions, and opportunities for value maximization when constrained by stem characteristics. Other aims were (i) to develop a methodology for integrating the various log merchandising decision levels which can be used for evaluating the trade-offs just mentioned; (ii) to demonstrate how the yield

assessment system and integrated planning framework can be used for modelling the multiple period merchandising problem; and (iii) to test the feasibility of utilising the log merchandising system. Such an integrated planning system should be robust, capable of being used in developing feasible plans for diverse log grades, able to react to changes in such log mixes in response to a dynamic market environment, and not require excessive computational overheads when used for modelling problems of realistic size.

There are three distinct facets to the development of an integrated log merchandising system: the first relates to the yield description system, which defines the bounds on production by log assortments; the second relates to the optimization of log mix production plans for different stands and periods, and; the last is the integration of strategies across the temporal levels of decision making.

Yield of stands is commonly described by log assortments for utilization planning. Existing approaches to yield description involve one of two approaches. The first one is to estimate the volumes by log assortments by evaluating the conversion of a sample of trees from a stand into market log grades using a bucking model.

However, because bucking models are formulated to solve for strategies that maximize value of individual stems, these are rarely optimal for a whole stand or forest. This is because such solutions do not take into account market constraints and the opportunity cost of producing logs from what is essentially a limited resource, and therefore unnecessarily constrain the optimization of log mix production. A variation of this approach is a column generation technique, which involves solving an integrated system of log allocation and bucking models iteratively.

Using this system, the yield description and optimization of outturn is performed simultaneously. However, the method has high computational overheads for the single period problem, and become prohibitively expensive to solve for the multiple period one.

The yield description method adopted in this study exploits the joint nature of log production. The method involves estimating potential outturn by evaluating the crosscutting of a sample of trees using a stem bucking optimizer. The major differences, however, lie in the log specifications used in the simulation, and in the log values used to control the optimization process within the bucking model. In this study, all marketable log grades are grouped into a few classes, each class of which is composed of log types requiring similar stem qualities. A bucking model is then used to determine the highest quality class

into which log length sections of stems can be cut, by evaluating the bucking of a sample of stems. The log values used to control the bucking simulation are determined heuristically as that which would result in the cutting of the highest possible volume of the class, but which does not lead to a reduction in the total volume of higher quality classes.

The effect of using such log values in a bucking simulation, is to characterize the stems into log length sections of the various quality class. The objective of the bucking simulation is therefore converted from one of maximizing stem value, to one of establishing upper bounds on production of the quality classes when constrained by stem characteristics. A log allocation model is then used to disaggregate the log quality classes into marketable log types, with downgrading employed as a marketing strategy for better balancing of supply and demand. A bucking model, *XCut*, suitable for performing such an outturn assessment was developed and implemented in Prolog as part of this study.

The major levels of decision making evident in the literature are short term log allocation and long term harvest scheduling. Log allocation models are used to evaluate short term marketing strategies, while harvest scheduling models are used to plan long term sequencing of stand harvests. They are frequently solved in anything but an integrated manner, and rarely include consideration of alternative strategies for stem conversion. Existing modelling approaches to integration of the various decision levels has mainly been to formulate a large model which incorporate consideration of all levels to some extent. A disadvantage with this approach is that the detailed levels are modelled in aggregated form, which does not provide sufficient detail for operational implementation. Another disadvantage of the method is that, data for future periods are uncertain, or can be forecasted only with a low precision at best, while those for nearer periods are more certain and can be forecasted with greater precision. It is, therefore, intuitively more logical to separate the uncertain longer term components of the modelling from the more certain short term.

The different planning levels were integrated with the hierarchical planning (HPP) paradigm in this study. HPP is based on the realization that there are different levels of decision making in organizations, which differ in management responsibility, scope, level of informational detail, length of horizon, and degree of risk and uncertainty. The main features of HPP are partitioning of the overall problem into smaller parts, with increasing aggregation of data at higher levels of modelling; separate models for each decision level, with

solutions from higher level models contributing to constraints in lower level ones; formalized linkages between sub-problems, with implicit stress placed on the interactions and linkages between the different models, and in designing models to fit well together. The HPP structure adopted in this study for modelling the multiple period merchandising problem comprises three different levels: a long term tactical model of 15-30 years, a short term tactical model of 2-5 years, and a quarterly (i.e 3 monthly) operational model.

The long term tactical model is concerned with scheduling stand silviculture and harvest, and with issues of sustainable production of the various log classes over medium term horizons. The data are aggregated into croptypes and log classes for the latter periods of the horizon, but disaggregated to the stand level for the earlier (up to year 5) periods. This model level corresponds to the harvest scheduling models in the published literature, and can take any of the model I or II forms (Johnson and Scheurman, 1977) or the model A form of (Garcia, 1990), with the last one as that likely to offer the greatest flexibility. The modelling formulation required is a standard LP.

The short term tactical model is concerned with providing more detailed harvest schedules of the stands from the first 2-5 years of the long term tactical plan, with quarterly period widths. This particular model was not developed as part of this study, but its features and possible model forms are discussed. It is concerned with such decisions as road and landing location and construction, and preliminary feasibility and planning of log production and distribution. A function of this level, therefore, is to disaggregate stand schedules generated by higher level models down to scheduling harvest at the setting or group of setting level. The objective at this level is to meet wood supply projections at minimal costs, including those of landing and road construction. Constraints on harvesting systems and crews are considered here. Demand is firmly modelled for the first few periods, but later ones are less rigidly imposed. The major decisions at this level require not only resource, harvesting crew, and market data, but also spatial and topographical information showing terrain characteristics. A possible fruitful approach to modelling this level, therefore, would appear to be a mixed integer program based on facilities location theory, interfaced to a digital terrain model and to a stand record system.

The lowest level model in the HPP structure is the operational model. It is concerned with allocating logs to meeting firm supply commitments and markets, and addressing the issues of harvesting crew availability, their allocation to stands scheduled for harvest, and detailed log production schedules for each stand. The solution provided by the model

includes the log mix to be cut from each stand in any time period, and crew allocations to stands scheduled for harvest in all periods. The planning horizon is one quarter of 13 weekly periods. A mixed integer LP for solving crew and log allocations was developed as part of this study. The formulation considers possible crew movements and the costs of such movements, and the optimal volume of each of the log types to be produced from each stand in every period.

Alternative formulations of the operational model, for evaluating multiple objectives, and for dealing with infeasibilities are also presented and discussed in the thesis. Multiple objectives can be evaluated by converting the formulation to a mixed integer linear goal programming model. Different objectives can be modelled in this case: for instance, value maximization, revenue maximization, and cost minimization. To deal with infeasibilities, one objective, in either a multiple or single objective case, would be minimization of the use of external resources required to make the problem feasible, the variables for which are built into the formulation. The activity of these variables indicates which resources and levels are causing the infeasibilities, and therefore need to be changed to avoid the infeasibilities.

A program, which can be used for generating formulations of the operational problem in an algebraic format suitable for solving with LINDO¹ (Schrage, 1991), and implemented in Prolog, was developed as part of this study. It takes as input three files indicating the stands identity, their yields by log quality classes, area available, unit harvesting costs; the number, relocation costs, productivity, and operating costs of available crews; and a vector of market demand and prices of all the log types in all periods of the horizon, and the quality classes from which each of the log types are obtained. The input data files required by the formulator have a simple and intuitive format that facilitates data entry and editing, and provides a flexible mechanism for formulating problems in reaction to changes in the production environment, or for sensitivity analysis. The output is a problem file in a format ready for solving with LINDO.

The data needs for the three level planning system can be met from current forest management inventory practices with little or no extra cost. In long term planning, stands which are below mid rotation age can be modelled as crototype aggregates, while those above this age would normally have had a mid rotation inventory, and therefore have unique stand yield estimates and should be treated as individual stands for harvest scheduling

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purposes. The disaggregation from croptypes to stands follows, therefore, standard inventory practices and requires no specialised routines. The short term tactical model is based on modelling harvests of individual and not aggregated stands. The operational model, however, is based on scheduling harvest of settings or group of settings, and yield estimates for these units may therefore be required, depending on the variability of tree characteristics within the stand. The outturn assessment system proposed here can be generated from existing MARVL PHI based systems, with extra effort required only in conducting the sampling in a manner that recognizes the variability at the setting or group of setting level.

An aspect of log merchandising that has received relatively little attention in the published literature is the interface between planning and field implementation. This has an impact on both yield reconciliation and in the control of field bucking. Current approaches to outturn assessment can be characterized as descriptive, and do not provide a mechanism for systematically controlling outturn during implementation. The only exception is the work of (Eng, 1982; Eng et al., 1986), who proposed a method involving solving for bucking strategies for various stem size and quality classes. However, the possible large numbers of such classes make the system difficult to use in both planning and field implementation. A method was developed in this study, which can be used for this purpose and also for testing the feasibility of cutting the planned log mixes.

The method involves reviewing the log specification which form the basis of a bucking simulation, in order to generate new specifications which when adopted, yields the volumes of each of the log sorts at levels recommended by the log allocation plan. The method is a heuristic procedure, based on selecting the most preferred lengths, and a revision of the minimum and maximum small end diameter limits. The latter is driven by the method of bisection, locating the minimum SED within a sequence of systematically smaller intervals. The new log specifications developed in this way are what are then used in field implementation, and are intended to drive the realized yields towards a planned log mix. The method leads to production of more uniform, higher quality material for each of the log types. The technique also offers an opportunity for controlling the average SED of each log type at the planning stage, which could be very useful as a quality control tool.

The planning system developed in the study was demonstrated and examined with a case study comprising a hypothetical forest for which long term tactical and operational plan

are to be developed. Both the long and short term tactical plans for this case were developed with FOLPI² (Garcia, 1990). The longer term plan had an horizon of thirty years, while the horizon for the short term model was three years, divided into twelve periods of one quarter. The solution for the first period of the short term plan is then fed into the lower level operational plan. The operational plan was developed with the formulator developed as part of this study, for the stands scheduled for harvest in the first quarter of the short term tactical plan. The plan provides a detailed solution for each week on harvesting crew allocations, productivity, movements between periods, and associated costs. The effects of these are therefore reflected in the log allocation and log mix production in the various periods.

The feasibility of producing the log mixes recommended in the operational plan was tested by revising the log specifications according to the procedure described above, which also provides new log specifications for use in field implementation. Using this procedure, the log mix proportions recommended in the operational plan were achieved to within a 5% tolerance of the planned volumes of each log type in all the periods tested. This was the case for not only random length log grades, but also for the fixed length grades, which are usually more difficult to model. Furthermore, the revisions resulted in cutting of logs that had an average SED well above the market specification for all the log sorts in all periods.

These results provide evidence for the practicality of using the outturn assessment system and demonstrate the advantages that the overall system provides for integrating quality control within the utilization plan. The selection of preferred piece lengths for particular log types at the planning phase were attempted in only a limited application in this case. However, the opportunity for manipulating piece lengths and other qualitative and quantitative log specifications are plainly evident. This offers resource managers a tool that could be useful for integrating quality control within utilization plans, and also provides a more rational basis for yield reconciliation. With the increasing requirements by markets for suppliers to provide improved quality certification within the industry, the potential advantages that this capability can offer resource managers cannot be overemphasized.

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6.2 Conclusions

From the foregoing discussion of the research and developments in this study, the conclusions below can be made.

1. The outturn assessment system presented in this study, together with the bucking model, *XCut*, developed to aid in such modelling, can form the basis for tackling the multiple period merchandising problem. It represents a potentially more useful alternative for making such merchandising plans than currently exists. Outturn assessment systems have been a major bottleneck to modelling the multiple period, multiple stem merchandising problem. The system proposed here enables this problem to be modelled with only minimal increases in complexity of the formulations, and with little or no increase in computational burden. The resulting models enable merchandising options to be modelled more flexibly, and have been shown to generate feasible plans. The outturn assessment system has the following advantages over systems presently in widespread use.
 - (a) The outturn assessment system characterizes the crop into quality classes, without the confounding effects of the market. It therefore provides a proper means of describing the qualitative features of a resource, and can therefore be used for valuation purposes, either with or without market constraints, with greater confidence.
 - (b) The outturn assessment system is robust, and provides greater flexibility in modelling log merchandising. Using the system, new cutting strategies for stands can be generated easily, for instance in response to changes in market demand, crew constraints and other factors, with comparative ease.
 - (c) The system is simple and easy to use, and results in the development of feasible cutting strategies, which can be modelled with linear programming and related techniques. Such models do not have the heavy computational burden characteristic of column generation techniques, while providing greater flexibility in generating log mixes than outturn assessment to fixed market log grades.
 - (d) The aggregated log types, which form the basis of the outturn assessment system, are relatively more stable than market log types, and are not sensitive to changes in market demand and log prices. They can therefore be used for yield projection in long term planning with a greater degree of certainty.

- (e) Because of the stability of the aggregated log types already mentioned, a stable benchmark is provided against which yield reconciliation and the level of achievement of value maximization goals can be measured, irrespective of prevailing market prices and to which outturn assessment to market grades are highly sensitive.
2. The framework for integrating the log merchandising planning levels based on the HPP paradigm adopted in this study is feasible and leads to a logical system of modelling the various separate decision levels. The HPP system offers greater flexibility in modelling the different planning levels than monolithic modelling approaches, and allows each level to be modelled at different resolutions of detail, with only minimal sacrifices in global optimality of plans. The system can be used for:
 - (a) modelling harvest scheduling, regeneration, and stand management options over the long term;
 - (b) operational market planning and stem conversion when constrained by harvesting crew and machinery availability and allocation;
 - (c) evaluating the conflicting requirements for resource based marketing in the long term and market oriented merchandising in the shorter term.
 3. Existing harvest scheduling models, such as FOLPI, can be used for modelling the long term tactical plan within the HPP framework. However, this modelling package may need to be adopted, e.g. with a log allocation and downgrading extension, in order to model the merchandising decisions if used in conjunction with the outturn assessment system presented here.
 4. There are no existing methodologies suitable for modelling the short term tactical level of the HPP framework proposed in this thesis. The kind of model required should have the capability to provide solutions of optimal location of landings and of road construction, which requires interfacing to digital terrain models, such as a GIS. The most appropriate form of model would appear to be one based on facility location theory. Because of the considerable special structure of such models, heuristic solution methods may be required for solving such models.
 5. The operational log allocation planning model and the accompanying program which can be used for formulating such models for solving with LINDO tm developed in this study offer a new method that can be used for planning short term log merchandising and harvesting crew movements to different stands or settings. The method

allows for the robust generation of feasible bucking strategies in each setting or stand in different time periods in response to market changes.

6. The goal programming formulation of the operational model which is also presented, provides a useful means for evaluating multiple objectives and for analyzing the causes of infeasibilities during initial runs. Such objectives as value maximization, maximizing crew utilization, minimizing the use of external resources, and minimizing deviations of log supplies from market demand levels can be modelled with no significant increase in complexity.
7. Mixed integer LP techniques have been shown to be capable of modelling operational log allocation plans, and the resulting models can be solved in reasonable time with existing general purpose mathematical solvers, even on personal computers. With recent advances in solution methods for integer problems, the rapid decreases in prices of powerful computers, and the increasing accessibility of more powerful computer systems, the use of MILP techniques in forest utilization plans is bound to increase.
8. The MILP operational model which utilizes integer variables for modelling crew availability and allocation, is a tight formulation, with a difference of under 0.1 % between the objective values of the continuous and integer optimal solutions to the case study problem. Thus there is some opportunity to develop single purpose heuristics for solving this formulation more efficiently than can be achieved from general purpose packages.
9. The system developed for controlling outturn and testing the practicality of log mix solutions from log allocation plans developed in this study functions satisfactorily, even for fixed length log grades which have proved difficult to model in the past.

The system as judged from the case study, offers resource managers the advantages listed below.

- (a) It provides a means for controlling outturn at the planning stage, by generating log specifications which, if used by field workers, drives recovered yield towards planned volumes. This would reduce the deviation of field bucked volumes and log mixes from planned levels of these, and can facilitate the process of yield reconciliation, which is a major problem in the industry;

- (b) It offers a systematic approach to planning and controlling quality right from the planning stage, which can be a valuable means for reducing quality variations within and between log batches. Because quality issues are beginning to assume prominence in log delivery, the use of the system for quality control alone may very well be an important contribution.
 - (c) As a corollary to the above, it offers resource managers greater flexibility for manipulating the average SED's of log batches delivered, either to increase or lower these as desired. Currently, there is no method used for systematically manipulating SED at the planning stage, but SED is a major variable for measuring the average piece size and quality of a log order.
 - (d) It offers a means for testing the feasibility of harvesting a given log mix plan from a stand without any harvesting, and for analyzing the effects that harvesting such log mix proportions have on the quality of the various log grades, a capability that is not evident in the published literature.
 - (e) Use of the system as a basis for planning log merchandising with LP models, especially of the operational planning type developed in this thesis, offers a mechanism for establishing a resource and market constrained internal transfer or opportunity prices for the various log types. The other outturn assessment systems already discussed can give an indication of such prices, but these are confounded by the limited log mix possibilities presented in the model. The outturn assessment system presented here establishes an absolute upper bound on production of the various log types, and by allowing the joint product nature of log production to be modelled in detail, offers a more comprehensive system for the establishment of log values.
10. Finally, the system of modelling the multiple period wood merchandising problem presented here offers managers a complete, new and powerful means for analyzing wood merchandising options within the long and medium terms that can be used for improving the profitability of forest production and utilization. The system of models can be used for analyzing any stage of forest production, and such management actions are reflected in subsequent runs of the lower level models, offering a fully integrated optimizing system. The use of such a system, moreover, is facilitated by the simple structure of the models at the different levels, which can be a major impetus to its adoption.

Chapter 7

Recommendations

The system of models developed and demonstrated in this thesis offers an enhanced modelling capability which resource managers can use in planning wood merchandising in the medium and short term. There is still some scope, however, for considerable research in areas related to the focus of this study, and some extensions and enhancements to the modelling system discussed here that could improve their utility for planning purposes. Specific suggestions for further work are listed here below.

1. The need for a model to disaggregate stand level planning to allow optimization of setting and landing constructions at the short term tactical level has been discussed, together with the possible issues that such a model could address. This important link in the hierarchical framework proposed here is an important one, as it would address one of the most expensive components of harvesting operations: road and landing construction. This type of model has not received much published attention since the work of Dykstra and Riggs (1976). It is likely to be the most complicated in this framework, as it would need to be interfaced to the resource database on the one hand, and to a system for representing topographical information, such as digital terrain models, for describing possible landing and road locations on the other. An optimizing model based on facility location theory, interfaced to a Geographical Information System (GIS), possibly by intelligent systems developed with knowledge based programming techniques would appear to offer the greatest promise in this regard. The recent work of Davis and Martell (1994) in integrating an LP forest planning model and a GIS for geographical representation of such plans points to

potential solution techniques. Other work potentially useful in this regard is in the meat industry (Whittaker and Brown, 1991) which involves interfacing a database management system to LP models for production planning.

2. The feasibility of plans developed by models based on the outturn assessment method proposed in this study would depend on the size and the accuracy with which an inventory sample represents the resource. Work on the most useful sampling methods for such inventories, and the minimum size of a sample required to represent a resource adequately is warranted as a means of improving the accuracy.
3. The methodology used for revising the log specifications for plans of log mixes developed by the log allocation matrix generator was tested by manually running components of the model components in series. Implementation of this procedure within a computer program for the automated development of new log specifications is required to improve its utility. Such a system could, for instance, have suitable tolerances to specifications that achieve target volumes of the various log grades, to improve solution time.
4. One area that requires substantial work with regard to forest planning models is the user interface. Most forest planning models, including the ones discussed in this thesis, are by the very nature of the planning problem addressed, complicated. They require data that are quite substantial, not only in variety, but also in quantity and level of detail. Preparing a single run of such models is therefore not only time consuming in the data preparation and entry phase, but difficult to run because of the model complexity. As most forestry enterprises now keep stand and other operating records in digital databases, there is great scope for building intelligent systems to access such databases to generate and solve the models, with the user only indicating to the system the resources to be modelled and the type of analysis required. Again the work of Davis and Martell (1994) and Whittaker and Brown (1991) point to potentially useful approaches.
5. There are some further extensions and developments that could be made to the operational log allocation model.
 - (a) Starting and ending inventories in the model are considered only by modifying the demand levels in the relevant periods. The model form does not allow for the evaluation of possible changes to the management of existing inventories, although this could be a viable merchandising option. Extensions to the

formulation to consider these factors maybe warranted.

- (b) The user interface issues discussed above also apply to this model. A report facility for interpreting solutions of the plans was not developed as part of the study. This would be required to make the model useful for operational planning, but could be considered more profitably within the overall context of user interface development. Development of interfaces to DBMS facilities for problem generation directly from these with only minimal intervention in problem specification and interpretation of results by the user would greatly enhance its use in planning.
6. The last recommendation is on the outturn control methodology developed in this thesis. The search phase during revision of log specifications uses the bisection method. Experience with this method shows that the solution can only be obtained in at least 3, but frequently more iterations, with considerable computation time. There is some opportunity for the development and use of more intelligent search strategies to reduce the overall number of iterations, and therefore computation time required for developing the new specifications.

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Appendix A

The XCut Stem Bucking Optimizer

A.1 Introduction

XCut is a single stem bucking optimizer (the acronym stands for CROSSCut) which was developed primarily for use in generating detailed pre-harvest information on how a resource can be converted into logs. The bucking optimization is based on a Dynamic Programming (DP) formulation, and was developed in the Prolog programming language. Inputs to the *XCut* model are two ASCII (text) files comprising a log grade specification and a stem data files.

The output from the model is a file providing an aggregate summary of the volume, value, average length and average small end diameter (s.e.d.) of each log type from all the stems in every simulation. The model also has an option which provides the optimal bucking strategy for each stem in the data file, if required. Entry of data into the input files can be done with any text editor, but must be in a format specific to the *XCut* model.

This section of this dissertation has the following three objectives:

1. To describe the mathematical formulation on which the *XCut* stem bucking model is based;
2. to describe and discuss issues relating to the implementation of the model, especially those that affect processing efficiency, and;

3. To give some insights into the model's development.

The third objective involves describing some of the features of the environment, Prolog, which was used for developing the model. As a programming language, Prolog has unique features which, in my view, makes it particularly suitable for developing specifications (prototyping) for this kind of problem, and for implementing such specifications in an easy and expedient manner. These features will be described, and then the potential uses to which Prolog can be put in the development of integrated Decision Support Systems (DSS) will be discussed.

The stem bucking problem can be considered as one of determining how to cut tree stems into logs in order to maximize the value of a resource. In the single stem case, this decision is constrained only by the unique form and profile of the stem, and by specifications (form and profile) and value of desired products (logs). In the multiple stem case, due consideration must also be given to demand and supply, in addition to the stem profile and end product demand constraints.

The single stem bucking problem is analogous to the well known one dimensional knapsack problem of Operations Research. However, there are two factors that make stem bucking unique in this class of problems. The first is that tree stems have variable taper and unique quality features, and each log type can therefore only be cut from specific parts of a stem. This is unlike uniform raw rolls in the commonly cited paper trim problem, for instance. In the paper trim problem, the uniformity of the material means that the decision variable is only the length and width of pieces to cut from the paper roll. A second unique feature of stem bucking in this class of problems, is the multiple nature of the units of measure: metres for stem length, centimetres for stem diameter, cubic metres for product size classes, and currency for value (Eng, 1982). The *XCut* model is formulated for the single stem problem only, but data from the model is intended for use in solving the multiple stem case as described in earlier sections of the dissertation.

A.2 The Dynamic Programming Formulation

The most commonly used analytical technique in single stem bucking optimization is DP, although models based on arc networks (Sessions, Olsen and Garland, 1989) and Branch

and Bound (Bobrowski, 1990; Bobrowski, 1994) have also been used. The underlying bucking optimizer in the XCut model is based on the DP formulation first described by Pnev-maticos and Mann (1972), which has since been implemented by Eng et al. (1986), Threadgill (1987), Lembersky and Chi (1986), and Deadman and Goulding (1979), amongst others. The basic scheme in this formulation is to evaluate the bucking at uniform, discrete intervals along the stem called stages. The evaluation is started at one end of the stem, and proceeds recursively in stages to the other. The decision required at each stage is the cutting strategy which would optimize the value of the stem up to that point, if the optimal strategy for the rest of the stem is known.

The stage is the basic unit of this evaluation, and the lengths of all the log types must therefore be multiples of the stage length. The definition of stage length used in this study is similar to that of Eng (1982) and Faaland and Briggs (1984) cited in Threadgill (1987): it must be a common multiple of all log types that can be cut from a stem, and it must also be less than or equal to the minimum difference in length between the candidate log types. The most commonly used stage lengths in New Zealand is 0.1 and 0.3 m (one foot), the common multiples for most log types.

The evaluation can start from either end of the stem, and iterate recursively to the other with identical results. Starting at the base of the stem is the most intuitively appropriate strategy, however, and is the approach used in the XCut model. It is argued by Eng (1982) that computationally, this is also the more efficient strategy, although any such efficiency gains are marginal. With each stage is associated a state and a state configuration. With the evaluation started at the base of the stem, there is a one to one conformity between state and stage, and the state is then the distance to that stage from the base of the stem. The state configuration is then the potential log cut, its quality, value, and s.e.d. At each stage, the required decision is the state which optimizes the value of the stem up to that point, and is called the optimal sub policy for that stage. The DP optimization iterates over all the stages in the merchantable portion of the stem, L_{MAX} , and produces an optimal sub policy for each stage. The optimal cutting strategy for the stem is the optimal sub policy at merchantable height, which corresponds to stage L_{MAX} .

Mathematically, the DP recursive relationship can be expressed as shown in Equation A.1, using the nomenclature of Eng (1982) and Eng et al. (1986). Figure A.1 shows how the DP recursion iterates over the stages using that nomenclature. Figure A.2 is an arc network representation of the DP bucking evaluation, with the stages as the nodes of the network.

Each arc $(L - y_k, L)$, represents a feasible log of length y_k which can be cut with the recursion at stage L (Eng, 1982; Eng et al., 1986).

$$f(L) = \max_{y_k \in Y(L)} \{r(y_k, L) + f(L - y_k)\} \quad (\text{A.1})$$

$$L = 1, \dots, L_{MAX}$$

and

$$f(0) = 0 \quad (\text{A.2})$$

where

- $f(L)$ = the maximum return from a log L stage units long.
It is the optimal return implied by state L
- k = a log type of known length and grade
- y_k = length (in stage units) of log type k
- $Y(L)$ = the set of feasible log types at stage L
- $r(y_k, L)$ = the value of a log bucked distance y_k from the
base of the stem
- $f(L - y_k)$ = the value of the optimal bucking strategy for a log
 $L - y_k$ stage units long

A.3 XCut Inputs and Outputs

There are two basic categories of input data to XCut model, log grade specifications and stem data. The log grade specifications are presented to the model in a log specification file, which has a fixed format. The specifications for each log type comprises a log type

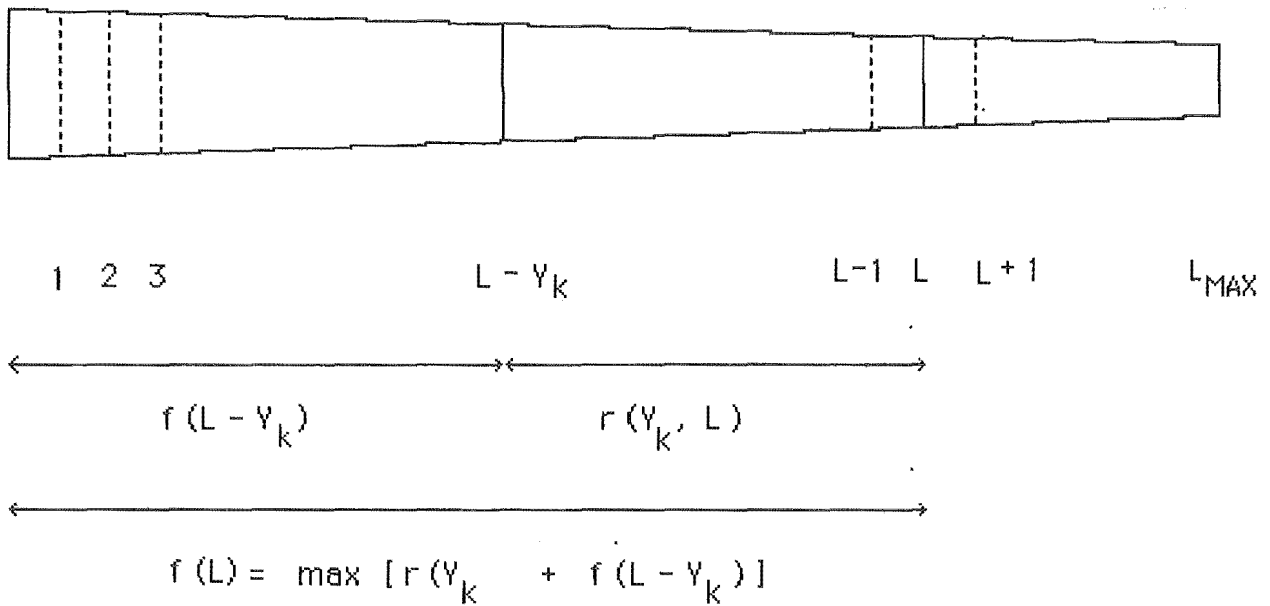
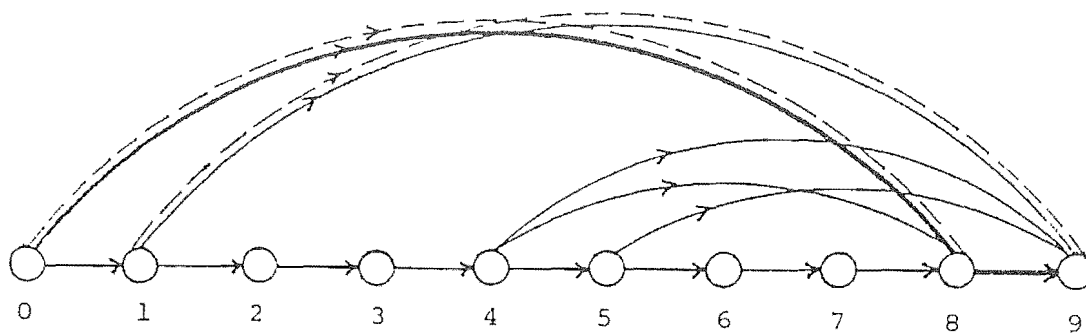
Figure A.1: The DP stem discretization (after Eng *et al.* 1986)

Figure A.2: Arc Network representation of the DP bucking. The nodes are the stages of the DP (from Eng [1982])

name, minimum and maximum allowable lengths, minimum and maximum allowable large and small end diameters (l.e.d. and s.e.d.), a list of allowable defects, and a unit log value. For each log type, it is assumed that logs cut can be of any length between the allowed minimum and maximum in increments equal to the stage length, unless fixed length requirements are explicitly specified.

The allowable defects, on the other hand, are entered in the file as alphabetic character codes, a different character for each defect type. In the current version of the model, there is no provision for specifying the magnitude of stem defects for bucking evaluation. Instead, the user can implicitly differentiate between acceptable magnitudes of a defect type, by classifying these under separate defect codes. It is intended to extend the capabilities of the model to allow for the explicit differentiation of magnitudes of defects in future versions.

The log value, ($\$/m^3$), can be a market price, or an artificial index that reflects the relative product preference of the user. If an artificial index is used in place of market value, the importance of objectively determining such indices is most important. This is because the DP optimization is driven by log values, i.e. ($Volume * Unit\ price$). The log values therefore determine the optimal bucking strategy for a stem, which in turn affects all subsequent processes, such as log allocation and conversion efficiency. It is only when two or more potential logs have equal unit values that secondary factors come into consideration. If the log types are of equal length, then the log type encountered first in the log specification file is selected as optimal. Further to this, a cost is assessed for making each saw cut. The effect of this is to encourage the bucking of long logs, instead of several shorter ones of equivalent value.

The second basic input to the model is a tree data file, which is the sole means of characterizing stems in a resource to the model. As XCut is intended as a pre-harvest inventory tool, the input data describe the form and profile of standing trees in a forest, while the model simulates processing of felled and debranched stems. For a bucking evaluation, stem profile is characterized by the diameter at breast height (over bark) (dbhob) of a tree. The other data necessary for describing stem profile, such as merchantable tree height and under bark diameters at stages along the stem, are then computed as a function of the dbhob, using taper equations specific to the tree species and forest locality. The under bark volume of a section between any two points along the stem can be determined with a volume equation. Alternatively, if a compatible taper model is used, then sectional volumes

can be determined by integrating the taper equation over the limits of interest.

Stem form, on the other hand, is considered as a series of features (or lack there of), describing deviations from a straight, defect-free bole, and occurring along explicitly specified parts of the stem. In the input data stream, each feature is described by an alphabetical character code, and starting and ending heights along the stem. Such features can overlap or be nested within a section of the stem covered by another feature. For instance, a large branch stub, or a stem wobble can be partially or wholly contained within a swept section of the stem. Each feature is recorded separately, using a code that must be similar to that used to represent the same defect feature in the log specification file.

The absence of any recorded features for a stem or stem section implies that the stem or section is straight and defect-free. Any feature recorded only as a code and a starting height, is inferred to occur from that point to the top of the stem. As an example, the line of data below would be interpreted by the model as specifying that the stem has a dbhob of 43.2 cm, and is defect free for the first 12 metres, has feature type "a" from 12.0 to 21.8 metres, feature type "b" from 15.5 to 19.3 metres, and feature type "c" from 20.0 metres to the top of the stem.

43.2 a(12,21.8) b(15.5,19.3) c(20)

In the log specification file, each log type has a list of features which are acceptable for the grade. The XCut model cuts a log type only along sections of the stem which is either straight and defect-free, or has features which are acceptable for that log type. Unlike the model reported by Eng (1982) and Eng et al. (1986) therefore, the set of feasible log types at stage L , $Y(L)$, is defined as including only those log types with permissible defects existing as features along the stem section (y_k, L) . The default log type, "waste", is always included in this set, as it can contain any defect. Consequently, there is no need to assign negative $r(y_k, L)$ [Equation A.1] values to any stem sections as in Eng (1982) and Eng et al. (1986), as these are bucked to log type "waste" if the features along this section are not compatible with the acceptable defects for any of the log types. All log types can however be cut from the straight and defect free sections of the stem, the only constraints being the large and small end diameters and the length of the section.

The treatment of stem form in the XCut model is the one major difference between this and

other implementations, such as those described in, for example, Deadman and Goulding (1979), Threadgill (1987), Eng (1982), and Eng et al. (1986). In Deadman and Goulding (1979), stem form is described in successive sections by quality codes. These codes indicate the suitability of the section for particular end uses (log types), arrived at by interpreting the features along the section according to permissible defect information for the log types. In Eng (1982), Eng et al. (1986), the form is described for each quarter stem section by codes, identifying the stem quarter and product suitability. For instance, the stem form described by the code 'T3SRP' would stand for "... top 3/4 suitable for sawlogs, remainder pulp logs ..." (Eng et al., 1986). Another major feature of this stem form description is the formation of 2 way stem dbhob and log type suitability class frequency tables. The bucking is then done on stem classes, that are then extrapolated over the whole tree population using the tree frequencies.

A major shortcoming of end product based stem form description is that resulting data may only be useful for specific or closely related problems. For instance, Eng et al. (1986) stresses the importance of matching the defect classification to the particular problem to be solved. As a consequence, data cannot be readily transferred from use in one project to another. Or, if the market forces major changes in end product requirements, a new field inventory has to be undertaken to provide data suited to the new problem formulation. Another shortcoming of the method is the resultant loss of detail in the data, when stem features are translated to broader end product codes. The effect of this is that if permissible defects for any end product change significantly, then the data may become invalid, necessitating a new field inventory. The method of describing stem form by features is a more robust approach, as it detaches the data collection from the problem formulation, making the data readily useable for a wider range of purposes.

A.4 Improving processing efficiency

In developing the XCut model, some techniques were used to enhance the processing efficiency of the bucking evaluation. These mainly involved eliminating processing of stages whose evaluation do not alter the optimal solution of the DP. One of these is setting the stage at which the bucking evaluation stops. The evaluation should theoretically be made either from the base to the top of the stem, or vice versa. However, stems taper towards the top, and once the diameter of the stem is equal to the smallest merchantable s.e.d. of

all the log types, then any extra processing does not change the optimal cutting strategy. This should mark the terminal point for the DP iteration. Conversely, if the evaluation is made from the top of the stem, then this should be the starting point of the evaluation.

Another factor which may affect the terminal point of the DP recursion, is that stems tend to break when felled. The break point is usually at two thirds the length of the stem, although this may vary with stand factors such as terrain, species and stem density. If the break point can be predicted, then again this should determine the terminal point of the evaluation. In the *XCut* model, the merchantable stem length, L_{MAX} , is determined either as the height at which the stem attains the smallest merchantable s.e.d., or the height at which the stem breaks when felled (as determined from suitable equations), whichever is the more constraining.

Another effect of variable taper is that once the stem diameter is smaller than the minimum s.e.d. for any log type, then that log type can be removed from the set of feasible log types, $Y(L)$ in Equation A.1. This is because the minimum s.e.d. restriction would become binding beyond this point, and it would therefore no longer be possible to cut the log type from the remaining portion of the stem. This has the effect of progressively reducing the set of feasible log types as the DP recursion progresses, thereby saving processing time. This technique has been used by Threadgill (1987), for instance. However, trials with this technique in the *XCut* model did not show any significant gains in processing efficiency. In the cases where a very large set of log types are being considered, this technique may lead to greater efficiency gains. The same technique could theoretically also be applied to the maximum s.e.d. and l.e.d. However, these restrictions are seldom binding, and are therefore unlikely to contribute significant efficiency gains.

Another efficiency enhancing technique that was found useful is in setting the stage at which the DP iteration is started. Theoretically, this should be at the base of the stem (stage 0). However, with the recursion proceeding from the base to the top of the stem, no cut can conceivably be made before the stage corresponding to the shortest log in the specification file, due to length restrictions. The bucking evaluation can therefore be started at this stage without any change in the optimal solution. In the *XCut* model, the recursion is started at one stage before that which corresponds to the shortest merchantable log in the specifications. All the stages before this are recorded as having optimal sub policies of log type "waste", with values equivalent to the cost of making a saw cut. For instance, in Figure A.2, if the shortest log type in the specifications is 4 stage units long, then no cut

can be made before this stage.

The most computationally demanding activities at each stage of the iteration are the determination of under bark diameters, and the integration of the taper equation to determine sectional volumes for all possible log types. During a simulation, underbark diameters at each stage and at the stage corresponding to the base of all log types in the feasible set are required in order to test for s.e.d and l.e.d. restrictions. If these and features along the stem section are acceptable, then the corresponding log volume is determined and used to arrive at a value for the log. These operations take a considerable amount of the CPU during each iteration. In the *XCut* model, the diameters at every stage and the sectional volumes between all succeeding stages along the useable part of the stem, are generated and stored in look-up tables indexed by stage number, before the start of an evaluation. The under bark diameter at any stage can then simply be obtained by retrieval from the tables. The sectional volume between any two stages is then obtained by retrieving and summing up all the sectional volumes between the two stages. In practice, this technique resulted in the most significant efficiency gains, and led to a threefold increase in processing efficiency.

A.5 Computational Experience

Solution times per stem of bucking evaluations with DP based models is heavily dependent on the number of log type - length combinations, the stem length, the stage length used, and the complexity of the taper and volume equations used. With the *XCut* model, the average solution time for a 32 metre stem, using a stage length of 0.3 metres is 10 seconds on an IBM PC compatible with a 80386 - 25 Mhz processor and no math co-processor. This is in comparison to a solution time of 5 - 10 seconds for an 8 Mhz IBM PC XT compatible with a co-processor for a similar sized stem and a stage length of 0.1 metres reported by Threadgill (1987) and 0.8 seconds on a Burroughs 6930 time share system with a stage length of 0.5 metres reported by Eng (1982) and Eng et al. (1986). On the surface, solution times for the *XCut* model looks adverse when compared to the reported ones, but this is not necessarily the case.

In the model reported by Threadgill (1987), the volume equation used is that for a frustum of a cone, with user entered sectional diameters. In the *XCut* model test case, on the other hand, the taper equation used to determine sectional diameters and which is also

integrated to determine sectional volumes, is a ninth order polynomial one. The computations required in the XCut model are therefore significantly more involved than that reported by Threadgill (1987). Another factor may be the number of log type-length combinations used in that study, which is not reported. In the XCut model, a total of thirty seven log type-length combinations were used for the test case.

With the model of Eng (1982) and Eng et al. (1986), there is a considerable difference in the computer platforms used, which makes the results not easily comparable. However, the longer stage length of 0.5 metres used in this latter model should theoretically result in a two fifths reduction in processing time over the XCut model. It is intended to transfer and implement numerically intensive parts of the bucking model, such as computation of sectional diameters and volumes, to C language modules interfaced with the Prolog code. This should result in a further reduction in solution time, as a result of access to numeric co-processor support, the rich C math library, and the overall efficiency of the C language in numeric processing.

A.6 The Implementation of XCut in Prolog

The XCut package has been developed in the Prolog Development Centre (PDC) - formerly Turbo Prolog - implementation of the Prolog Programming language (Borland Inc. and Prolog Development Centre, 1986-1992). The Prolog language is based on logic programming paradigms, and was developed in the early 1970's in France. It remained in research laboratories, largely, until 1981 when the Japanese announced it as being at the core of their Fifth Generation Computer System (FGCS) project (Sterling and Shapiro, 1986), (Bharath, 1986). Since then, many commercial implementations of the language have appeared running on different computer platforms, with the Edinburgh Prolog syntax as described in Clocksin and Mellish (1984) emerging as a *de facto* standard (Sterling and Shapiro, 1986). Commercial applications developed in the language have since proliferated, with most of these being implementation of Artificial Intelligence (AI) paradigms such as Expert Systems. New languages based on Prolog, such as Parlog, Concurrent Prolog, and KL1, have also since been developed, particularly for computer architectures based on parallel processing (Fuchi, 1992; Bharath, 1986).

Prolog programs can be described as being "...a set of axioms, or rules, defining relationships between objects ...", and therefore, "...computation of logic programs is a deduction of

consequences of the program . . ." (Sterling and Shapiro, 1986). Programs developed in conventional languages such as FORTRAN, Pascal or C define a sequence of statements or procedures that the program must follow to perform a given task. Programming in these languages has therefore been described as being "*imperative*" (Bharath, 1986). In Prolog, however, a program is defined as a series of facts, and the rules that describe relationships between these facts, collectively called *clauses*. Programming in Prolog is therefore declarative, and the only program logic is given in the form of facts and rules. No advice need be given to the computer on how to handle these. There is therefore no differentiation between data and program, flow of execution being built into the language through a backtrack mechanism.

Despite its declarative nature, features that are common in conventional languages, such as control of the execution path (iteration and conditional execution) and Input/Output (I/O) functions can be implemented in Prolog. The execution path can be controlled by discriminatory clause ordering for instance, and it has an extensive library of in-built functions that can be used to produce such "*side effects*" as I/O, or evaluation of arithmetic expressions. A useful introduction to the Prolog language is given in Bharath (1986), in which the essential features of the language and its differences to conventional programming languages, and the Prolog inference mechanism is also discussed.

Because of its declarative nature, Prolog programs are typically easy to read, and allow for concise and elegant formulation of problems. Such programs usually require less development time and fewer lines of code (typically only a third) than that of conventional languages (Marcus and Arity Corp., 1986). Prolog also requires much less learning time, as the language has only a few rules of syntax. Its high level nature allows a developer to be concerned with the problem to be solved, rather than how it is to be solved. Consequently, Prolog has sometimes been seen as providing "*something for nothing*", but because of its high level nature, programs may require substantially greater solution times. This is because Prolog processes clauses from Left to Right, and in a depth first pattern in order to prove a goal. Consequently, combinatorial searches are made to reduce the solution space, which may be quite large especially if the rule set is inconsistent. Furthermore, due to the uniformity of data and program, sections of the code must be reinterpreted at run time, thereby increasing solution times. The need for programs to run in real time may therefore require a recourse to some procedural programming techniques to speed up solution times. However, with the continuing exponential advances in computer hardware

technology, the slower execution times of Prolog code is increasingly becoming insignificant.

A feature unique to Prolog, as opposed to conventional programming languages, is that programs can self modify at run time, due to the uniformity of data and program. Other interesting features of the language are its powerful search and inference, and in-built pattern matching mechanisms. The language has sophisticated data structures, and the capability to manipulate and modify these, even at runtime. It has an in-built database, in which information can be stored by both the program and user at run time. It also has an external, dynamic database, which can be stored in files, on disk, and in virtual memory. Because of these features, Prolog is particularly suited to symbolic processing. It has found extensive use in the development of intelligent database management systems, Expert systems, and Natural language processing (Marcus and Arity Corp., 1986; Sterling and Shapiro, 1986).

However, the PDC Prolog dialect has features which make it essentially different from the Edinburgh standard, as described by Clocksin and Mellish (1984). The major differences are that PDC Prolog is a strongly typed language, and all clauses must be declared before they are called. The implementation also does not support rule assertion, and operator based grammars. This is in contrast to Edinburgh Prolog, which is a declaration free, typeless language (Sterling and Shapiro, 1986). Consequently, there is a break down in the uniformity of data and program code in this Prolog implementation. The ability of programs to self modify at run time, called *meta-programming*, can therefore be programmed in the implementation, but is not built into the language as is the case in Edinburgh Prolog.

The main gain from these features of PDC over Edinburgh Prolog, is an increase in processing efficiency. This results from elimination of the need to reinterpret sections of the code at run time, and also by a reduction of the solution space through typing. Typing also assures easier code debugging. Other extensions to PDC Prolog include good support for floating point operations through software emulation, although there is no numeric co-processor support. It also offers an extensive toolbox library, with a full screen extendable editor, which can be invoked in applications by a single function call. It also has utilities for handling strings, windows, menus, files, sophisticated graphics routines, and supports high resolution video outputs.

A.6.1 Prolog as a development environment

The major advantages that were experienced with using Prolog as an environment for developing the *XCut* model were, ease in formulating specifications for, and in the actual implementation of the model. The mathematical formulation of the stem bucking problem is widely available in the literature, for example Eng (1982), Eng et al. (1986), Deadman and Goulding (1979), and Pnevmaticos and Mann (1972), amongst others. However, the detailed implementation of the bucking algorithm had to be developed as work on the model progressed. Consequently, the development of the model involved trying out different methods of performing several operations, and making numerous changes to the code. Prolog's advantages over conventional programming languages became apparent in this regard. Prolog clauses are modular, and can easily be modified, with only a change in the side effects of the program, with little need to change the data structures.

One major advantage of Prolog programming is that it leads to explicit definition of the relationship between different parts of the problem. Due to declarative programming, Prolog forces the developer to be concerned only with describing the problem, and the relationships between different parts of the problem. No consideration need be given to program flow at all, until much later in the development cycle, when optimizing for processing efficiency. This results in very concise and elegant formulation of the problem specifications.

Prolog's excellent database and functions for manipulating these makes it easy to modify sections of the program, with very little consideration being given to data structures. It is therefore easy to try out alternative methods of performing operations, as any major modifications to the program can be done simply by adding, removing or modifying a clause, and the database can be consulted from any part of the program. A further advantage in this regard is PDC Prolog's extensive toolbox library. This has file, window, and string handling predicates, which can be included easily in applications by a single function call, and saves a lot of development time.

A major disadvantage of declarative programming is the processing speed of resulting programs. To improve this requires resorting to a procedural interpretation of such programs, examples of which are described by Kowalski (1979). The techniques which were found most useful in this regard mainly involve controlling the execution path of the programs, in order to reduce the solution space. The technique which was most useful in this

regard was discriminatory goal and clause ordering: Goals and clauses, when ordered in an appropriate sequence, cause early and efficient failure of the clause or goal. For instance, clauses or goals which require repetitive computations, such as iteration or recursion, should be put as far back in the clause or goal body as possible. This will mean that the goal may frequently fail before such clauses are evaluated, saving processing time. The same should be the case for sub goals in a rule.

Another technique that was found useful is to exploit Prolog's excellent database facility as much as possible. This can be achieved by initially consigning frequently computed values in the database, from where the values can be retrieved whenever required. An example in the XCut model is sectional diameter of the stem at any stage, which is required at least once, but frequently more times in every stage during evaluation. The same is also the case for sectional volumes. These computations take a considerable amount of time to perform, and when done repeatedly, significantly increase solution time for each stem. Such frequently used values are more efficiently computed once and stored in the database for look up whenever required.

The use of failure driven iteration, other than recursion, was another useful technique. In Prolog, recursion is the most natural way to express iteration. But, because of overheads in processing non-deterministic clauses, it is actually much slower and is much more demanding on the hardware, and can cause frequent and fatal stack overflow errors. The faster and more memory efficient way to implement iteration is to intentionally cause a clause to fail, and thereby make Prolog's efficient backtrack mechanism perform the iteration.

A.6.2 Potential of Prolog for the future

Prolog's acceptance as a language for developing AI applications is increasing worldwide, but this has not always been the case. In the mid eighties, the few numbers of major applications developed in the language, relative to other AI languages such as LISP, were used as a justification to categorize Prolog as a fad that would quickly wear off (Bharath, 1986). But Prolog applications now abound, with excellent examples in such wide fields from aircraft manufacturing, to despatching forest fire fighters. Keyes (1991) describes some of these commercial applications, which include a US Air Force system for optimizing loading of military air cargo, Boeing Corporation's system for keeping track of aircraft parts

specifications, a system for modelling molecular structure, an expert system for developing troubleshooting systems for electronic circuits, a system for scheduling building maintenance, and a system for representing, storing and tracing lineages of patients with chromosomal defects. Prolog applications are just as common in Natural Resource Management. Kourtz (1990) describes a system for optimizing the despatch of forest fire fighting equipment and personnel, and Kourtz (1989) describes a system for predicting forest fire occurrences. Koten et al. (1991) describes an integrated DSS under development for harvest scheduling and wildlife habitat evaluation, which incorporates a Knowledge Base, a Geographic Information System, and a database management system. Rauscher and Backer (1989) presents a survey of 93 AI applications in Forestry, of which 30 are developed in Prolog. Prolog's role in this field is already considerable, and continues to grow, due to the versatility with which various models for representing knowledge can be developed in the language.

A role commonly played by Prolog in the above applications is that of executive routines that drive, interconnect, and act as a data access medium for sub programs developed in other languages or proprietary application packages. This is the case with the system described in Kourtz (1990), Koten et al. (1991) and the Boeing Corp.'s data access system, for instance. The reasons for this are twofold. One is the need to use data from diverse, existing applications, and the second is the need to match available tools to appropriate problems. The first reason points to the excellent capabilities of Prolog for accessing and manipulating symbolic data, and this is another area where Prolog will continue to find extensive use. The development of integrated DSS requires data exchange between diverse applications such as database management systems, Geographic Information Systems, and Optimization models. This need is critical in forestry, with the need to access historical databases collected over many years of forest management, and has also been stressed by Kailo and Saarenmaa (1990). The other reason is to do with matching tools to problems, and especially with regard to Prolog's inadequate capability in numerical processing.

As has been previously mentioned, a weak area of Prolog is numerical processing, and lack of the excellent library of floating point routines that are usually a forte of most procedural languages, such as FORTRAN or C. On the other hand tasks such as meta programming and symbolic processing are more easily implemented in Prolog than in procedural languages. A more powerful and versatile development environment than stand

alone Prolog can be obtained by linking Prolog programs with routines in other programming languages. This approach to extending the power of Prolog is receiving increasing attention, and can be implemented fairly easily once the internal data representation of the other language is known. For example, Entsminger (1991) describes how C language routines can be accessed from Prolog, and Howe (1991) discusses how data within a COBOL program can be accessed from an overlying Prolog Expert System. This then gives the developer the benefits of a high level, declarative, logic-based language that can be used in overall program control or in routines requiring symbolic data manipulation. At the same time, the developer gains access to the library and functions of a procedural language, which can be used for numerical processing and developing low level routines. Such a system can be very useful in the development of integrated DSS. In many cases, for instance Howe (1991), this eliminates the need to duplicate applications already in use and developed in other languages.

Another area where Prolog has potential is in the development of intelligent interfaces. Decisions in forestry are made in a complex environment, due to the long planning horizons associated with decisions, the complex interactions of factors that influence tree growth and its economics, and the "confused" interaction of the participants in such decision making (Jeffers, 1989). This has resulted in forest managers using a wide variety of models to assist their decision making, which often have little or no interaction between them. Latter day decision support models in forestry are incorporating more and more such linkages, resulting in increasingly large and complex systems. Such complexity is further abetted by the rapid advancements in computer hardware and software technology. The result are models which better reflect the complex interactions of forestry systems, but which may become intimidatingly difficult for managers to use. There exists a recognized need for development of intelligent interfaces to such models. Such interfaces would guide users in formulating problems, assist in data input, and interpret the complex outputs from the model into contextually useable form for the non technical user.

Prolog was selected as an environment for developing the XCut model with the aim of facilitating the integration of, and data exchange between the model, and other forest management planning tools being developed as part of the project. Prolog as a programming language has previously not found much use in OR circles, although widely used for developing AI applications. The experiences encountered with the language were favourable, and suggest that the language has potential for use in the development of Decision Support Systems, especially when interfaced to procedural language routines for numerical

processing. With its strengths in symbolic data manipulation, it has potential for use in the development of executive and data exchange routines. Forest Management planning models are increasing in complexity and size, with consequent increases in difficulty of use. Prolog has great potential for use in developing intelligent and friendly user interfaces to such Mathematical Programming models, which can make such models more readily useable by managers who are not experts in OR.

Appendix B

Files on the appended diskette

The diskette which accompanies this thesis contains additional appendices, which include the programs developed as part of the study, sample input files for the programs, input data for the various models in the case study, and summary tables of and outputs of both the programs and for the case study. Table B.1 contains a listing of the names and descriptions of the files in the distribution diskette.

The files are all contained in the file THESIS.EXE in a self extracting, compressed format. These can be extracted by typing:

```
A: \>THESES
```

at the DOS prompt. All the executable program files will run only on IBM compatible Personal computers. All the other files are ASCII text files, which can be viewed with any text editor, but the diskette is written in MS DOS format. The formats of data in the files are included as comments at the top of each file. Before using any of the files, please note the contents of the READ.ME file.

Table B.1: Files on the Distribution Diskette

Name of File	Description of Contents
MYIELD	FOLPI input yield tables for the medium term case study problem
MSUM	FOLPI harvest schedule summary report for the case study medium term tactical plan
MSTATUS	FOLPI report on the status of the resource by period for the medium term tactical plan
SYIELD	FOLPI input yield table for the short term case study model
SSUM	FOLPI harvest schedule summary report for the short term tactical plan
SSTATUS	FOLPI report on the status of the resource by period for the short term tactical plan
XCut.EXE	<i>XCut</i> executable file
XData.DAT	Sample <i>XCut</i> input data file
XSpec.XSP	Sample <i>XCut</i> log specification file
XOut	Sample <i>XCut</i> output
QMAF.EXE	Executable (*.EXE) file of the operational model problem formulator for LINDO
QCASE.CSE	Case File for the case study operational model
qCREW.CRW	Crew file for the case study operational model
QMKT.MKT	Market file for the case study operational model
QCASE2.CSE	Case file for infeasible case study operational model
QCREW2.CRW	Crew file for infeasible case study operational model
QMKT2.MKT	Market file for infeasible case study operational model
READ.ME	Contains further information on the file formats